Comparison of Processes in Hydrologic Models
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ABSTRACT

The City of Austin Watershed Protection Department investigated the computational methods used to estimate hydrological processes employed by eight models. Processes examined include precipitation, interception, evapotranspiration, infiltration, surface runoff/overland flow, groundwater routing, and channel routing. Model templates were developed for comparison and may be used for additional models should the need ever arise to compare a new model to the current list. Models were evaluated on the number of processes employed, empirical nature of each process, and validity of processes used within the model. Several options are presented for model selection at the watershed, site, and individual structural control scale. The highest recommended options were to use the Gridded Surface/Subsurface Hydrologic Analysis tool to model hydrologic processes at the watershed and site scale, while the HP1 tool could be used to model individual structural controls.

INTRODUCTION

The City of Austin (COA) Watershed Protection Department (WPD) embarked on an effort to have calibrated water quality models for every watershed in the Austin area to initiate Objective 0 of the WPD Strategic Plan (Herrington 2017). The first part of this effort was to devise a modeling strategy, including the selection of a hydrologic model(s) and a water chemistry model(s). It was decided that the models used for hydrology and water chemistry need not be the same model. As it is easier to calibrate a hydrologic model than to calibrate a water chemistry model, WPD staff made a decision to examine a hydrologic modeling solution first and a water chemistry model solution second. This report provides a technical review of computational methods used in several common models used to simulate hydrology. Models reviewed include: Gridded Surface/Subsurface Hydrologic Analysis (GSSHA) (GSSHA), Hydrus 1D/PHREEQC (HP1) (Jacques and Simunek 2005), Hydrological Simulation Program – Fortran (HSPF) (Johanson et al. 1980), MODFLOW (Hughes et al. 2017), a COA Parsimonious model, Soil and Water Assessment Tool (SWAT) (Neitsch et al. 2011), StormWater Management Model (SWMM) (EPA. 2010), and VFlo (Vieux 2018). The SWAT model can be run with daily or sub-daily data but only the sub-daily version was considered.

METHODS

In order to compare each model in an orderly manner, a template was created that included general model information such as model history, watershed configuration, weather related inputs, and computational methods for simulating interception, evapotranspiration (ET), infiltration, surface runoff/overland flow, groundwater routing, and channel routing (Appendix A). Individual manuals were examined initially for information and model code was examined secondarily in open source models if information was not readily available in the model documentation. Full details for each model are available in Appendices B-I.

The WPD wishes to simulate physics-based hydrological process through structural controls, at a site scale, and at a watershed scale. Thus, comparisons and model recommendations were done at each of the above scales. Computational methods that were physics or theory-based were judged more desirable than highly empirical based computational methods so that calibrated model information could be transferred to controls, sites, and watersheds where no calibration data exists. A summary of hydrologic processes is presented with a recommendation for model selection.

RESULTS & DISCUSSION

Precipitation/Interception/Evapotranspiration

Precipitation is a required input for all the models; however, data entry and the level of complexity associated with that data varies from model to model. MODFLOW, HP1, and the Parsimonious model take a single time series in a spreadsheet format and apply the precipitation equally across the land area in the model. Precipitation time series are also entered for HSPF and SWMM; however, multiple spatially varying time series can be entered. The SWAT model can either use a time series of precipitation or simulate precipitation based on statistical data provided by the user. The VFlo model requires precipitation data in every surface cell in the model grid area and is typically supplied from radar predictions of precipitation. The GSSHA tool requires precipitation either be supplied via specifically located rain gages which is then distributed across the modeled area using either Thiessen polygons or an inverse distance square weighted method or be simulated through a design hyetograph.

Interception is not calculated in SWMM, VFlo, or MODFLOW. This will mean that a larger volume of water is available for infiltration/surface runoff in these models when compared to reality for areas with vegetation. The Parsimonious model incorporates interception into its abstraction method while GSSHA and HSPF use empirical user defined parameters to calculate interception. The HP1 and SWAT models have the most sophisticated procedures for calculating interception using the leaf area index of plants. In addition, SWAT incorporates the time in a plants growth cycle.

Evapotranspiration is currently unavailable in the Parsimonious model. The VFlo model requires the user to compute the ET and enter the data as either a single constant, single time series, or multiple spatial time series. MODFLOW incorporates the UZF package which calculates the ET based on several user defined values. The SWMM model has an option for the user to supply ET as a single constant, set of monthly averages, or a single time series; however, SWMM also has an option to compute the ET based on temperature data within the model using the Hargreaves method. The HP1 model calculates the ET using either the Penman-Monteith or Hargreaves equation (user specified option). The SWAT, HSPF, and GSSHA models use a potential ET initially and adjust that value to an ‘actual’ ET based on water in the soils. The potential ET is inserted as a time series in HSPF while the potential ET is calculated in SWAT (Hargreaves, Priestly-Taylor, or Penman-Monteith) and GSSHA (Penman-Monteith).

Infiltration

Common equations to calculate infiltration include Horton’s equation (an empirical formula which starts with an initial infiltration rate that decreases exponentially with time until the rate levels off at a minimum value), Green & Ampt (uses a function based on a wetting front soil suction head, porosity, hydraulic conductivity, and time), and Richard’s equation (uses a function based on the water pressure head, water content, hydraulic conductivity, and time). An advantage of the Richard’s equation is that it most closely matches physical reality but can be difficult to compute and convergence issues may develop when attempting to find a solution. The SWMM model allows users to pick from Horton’s equation, Green &

Ampt methods, or Curve Number methods to calculate infiltration. The VFlo model uses the Green & Ampt method while the SWAT model uses a modified version of the Green & Ampt method. MODFLOW uses a simplified Richard's Equation via the UZF package. The GSSHA model allows users to choose from the Green & Ampt method or Richard's equation. The HP1 and Parsimonious models use the Richard's Equation to calculate infiltration. The Parsimonious model first computes runoff using the SCS Curve Number method and then infiltrates water. The HSPF model empirically calculates infiltration based on a user defined minimum and maximum infiltration capacity.

Surface Runoff/Overland Flow

The HP1 model allows water to pond at the surface instead of calculating surface runoff. The Parsimonious, SWMM, SWAT, and HSPF models are considered lumped models while the GSSHA, VFlo, and MODFLOW models are considered gridded models. Lumped models generally have land segments that represent large surface areas while the gridded models are represented by cells at a much finer scale. An advantage of a gridded model in our application would be inserting SCMs at their actual functioning locations and obtaining resultant cumulative hydrographs at any point in the drainage system. Surface runoff in the Parsimonious model is calculated using the SCS Curve Number method. The SWMM, SWAT, and HSPF models first calculate the amount of water that is infiltrated and allow excess to be considered for runoff. The SWMM and HSPF models will allow the excess to pond at the surface and will only runoff if the depth of the ponded water exceeds a maximum storage depth set by the user. The SWAT model allows all excess to runoff. All three models use a variation of Manning's equation to calculate the flow of the surface runoff. The GSSHA model is similar to the SWMM and HSPF models, in which ET and infiltration are calculated and excess water is available for surface ponding and runoff. A depression storage may be set by the user and runoff will not occur until that depth is met. Routing to other overland grid cells is based on a 2-D solution of Manning's equation using a diffusive wave approximation. The VFlo and MODFLOW models compute runoff once the rainfall intensity rate exceeds the infiltration rate of the soils.

Groundwater Routing

The HP1 and VFlo models do not incorporate groundwater into the simulation so once water infiltrates the soil it will exit the simulation. The Parsimonious model does not route water to a deep aquifer but calculates lateral flow through a saturated zone via the Boussinesq Equation (Appendix F). The GSSHA and MODFLOW models use Darcy's Law to route groundwater through an underground 2-D and 3-D grid, respectively. The use of Darcy's Law should be adequate for groundwater routing if proper conduits can be built into the model structure. As both GSSHA and MODFLOW are gridded systems, they should allow for flexibility when building the groundwater structure of the model.

The HSPF, SWAT, and SWMM models have more empirically based groundwater routing and are thus less appealing. The HSPF model routes water laterally and downward into a "groundwater layer." Once in the groundwater layer water moves into either the active (still part of the simulation) or inactive (lost in the simulation) groundwater. The fraction of water that travels laterally and the amount that is considered to be in the inactive groundwater is set by the user. The SWAT model routes water through up to 10 soil layers. Water moves downward to the next soil layer if water content within the layer exceeds the field capacity for that layer and the layer below is not saturated; however, lateral flow occurs if the layer below is saturated. If water passes through all 10 layers, then it enters the "shallow groundwater" where it will either return to the creek or exit the simulation based on a user-specified threshold. The SWMM model passes water from an un-saturated soil zone to a saturated zone where it can move laterally or exit the simulation by moving downward. The lateral movement of water is a function of the height of water in the saturated zone and in the channel connected to that saturated zone.

Channel Routing

The St. Venant equations are typically considered when estimating flow within a channel. These equations are complex and typically require programs to use an approximation method to solve. Common approximations include the kinematic, diffusive, and dynamic wave methods. Kinematic approximations are acceptable when inertial and pressure forces are not important or when channel slopes are steep and backwater is negligible because gravity is driving the motion. Diffusive wave approximations are acceptable when pressure forces become important but inertial forces are still negligible or on milder slopes (≥ 0.01%) and backwater is limited. Dynamic wave approximations are considered ideal for situations where both pressure and inertial forces are important or when the channel slope is low and there is a large impact from backwater. In general, backwater will likely impact flow in Austin streams where they meet Lake Austin or Lady Bird Lake; however, the Diffusive wave approximations should be acceptable for modeling the large majority of Austin streams. The HP1 and Parsimonious models do not have any form of channel routing and are thus not useful for modeling at the watershed scale in their current form. MODFLOW uses the Kinematic Wave approximation to calculate flow within rectangular channels. The SWAT model allows users to choose between variable storage or Muskingham equations (variation of the kinematic wave approximation) to calculate flow within trapezoidal channels. The VFlo model uses the kinematic wave approximation to calculate flow but allows the user to define the channel as trapezoidal, simulate channel geometry using a rating curve, or input measured channel geometry. The HSPF model attempts to estimate the total outflow volume from the model through empirical subroutines. The GSSHA model uses the diffusive wave approximation to calculate flow and allows the user to set the channel as either trapezoidal or define channel geometry based on measured x-y pairs. The SWMM model allows the user to choose from steady state, kinematic wave approximations, or dynamic wave approximations to calculate flow in channels of standard and irregular shapes. Both the GSSHA and SWMM models allow for the modeling of closed stream networks (i.e., storm drain network).

Final Recommendation

The WPD staff discussed each of the above hydrologic components and made recommendations on the use of each based on the empirical nature and complexity of each process used within the model (Table 1). Components that rely on physics or theory-based computations were judged as desirable and marked with an X while components that rely on empirical computations were judged as less desirable. Every component of the GSSHA tool was recommended by staff. The GSSHA tool can be used for single events or long-term simulation at the control, site, and watershed scales. While the GSSHA is capable of simulating hydrology at the control and site scale, it should be noted that HP1 was highly recommended for single events or long-term simulation at the control scale due to the impressive hydrologic computations and its geochemical modeling abilities that are not discussed within this report. Due to its simplicity, the Parsimonious model was recommended a secondary option for modeling single events at the site scale.

Table 1: Recommendation of each hydrologic component within each model and the scale at which the model could be applied. An X means that the model is recommended for a component. In regards to scale; C = structural control, S = site, W = watershed.

Model	Precipitation	Infiltration	Surface Runoff/ Overland Flow	Groundwater Routing	Channel Routing	Scale
GSSHA	X	X	X	X	X	C, S, W
HP1	X	X				C
HSPF						S, W
MODFLOW		X		X		W
Parsimonious		X	Maybe	X		C, S
SWAT	X	Maybe	Maybe			S, W
SWMM		Maybe	Maybe		X	S, W
VFlo			X		X	W

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APPENDIX A: Generic template to compare model hydrologic processes.

Name of Model

General Information

Model History
(Original purpose of the model, who created it, date of origination, any changes over the years.)

Source (Open/Proprietary)
(If proprietary include fixed/subscription cost)

Maintenance
(Who maintains the model?)

Model Uses

1. Hydrology, nutrient transport, sediment transport, other pollutants?
2. How are SCMs incorporated?
3. Duration of Model Run
    a. Minimum/Maximum Time Step

Calibration Method

Suggested Tools for Data Entry

Watershed Configuration

Land Surface
Area to be simulated:

Land unit distribution: Gridded or Lumped

Hydrologic unit(s) of land whose topography and drainage system elements direct surface runoff to a single discharge point:

- Minimum/Maximum Unit Size:

Distribution of Impervious/Pervious Land:

Flow Pathway
Inflow or Discharge Points:

- Points of Interest

Primary flow pathway (channel, pipes, etc.):

- Points of Interest

Additional Information

Weather (include time step for applicable fields)

Rain:
Temperature:
Evaporation:
Wind Speed:
Snowmelt:

Climate Change:

Surface Runoff and Soil Routing

Inputs/Outputs
Precipitation
Surface Runoff
Infiltration
Evapotranspiration
Percolation
Lateral subsurface flow

Channel Routing

Description

Ground Water Routing

Description

Additional Information

APPENDIX B: Hydrologic comparison template for the GSSHA model.

Gridded Surface/Subsurface Hydrologic Analysis (GSSHA)

General Information

Model History

Gridded Surface Subsurface Hydrologic Analysis (GSSHA) is a physics-based, distributed, hydrologic, sediment and constituent fate and transport model. Features include two dimensional (2D) overland flow, 1D stream flow, 1D infiltration, 2D groundwater, and full coupling between the groundwater, shallow soils, streams, and overland flow. Sediment and constituent fate and transport are simulated in the shallow soils, overland flow plane, and in streams and channels. GSSHA can be used as an episodic or continuous model where soil surface moisture, groundwater levels, stream interactions, and constituent fate are continuously simulated. The fully coupled groundwater to surface-water interaction allows GSSHA to model basins in both arid and humid environments (https://www.gsshawiki.com/Overview:Overview).

The GSSHA model is a reformulation and enhancement of the CASCade 2 Dimensional (CASC2D) model, which began as a 2D overland flow routing algorithm developed and written by Professor P.Y. Julien, Colorado State University. The overland flow routing module was converted to FORTRAN by Dr. Bahram Saghafian, then at Colorado State University, with the addition of Green & Ampt infiltration and explicit diffusive-wave channel routing. The FORTRAN code was reformulated, significantly enhanced, and rewritten in the C programming language by Dr. Saghafian at the U.S. Army Construction Engineering Research Laboratories. In 1995, CASC2D was redesigned to include the addition of continuous simulation capabilities and ability to interface with the Watershed Modeling System (WMS) graphical user interface developed by the Environmental Modeling Research Laboratory (EMRL) at Brigham Young University (BYU). Overland sediment transport was added in 1997. Development of the CASC2D model for WMS by the Department of Defense (DoD) ended with version 1.18b, which was the basis for the GSSHA model (https://www.gsshawiki.com/Overview:History).

While developed from the CASC2D model, the GSSHA model is inherently different in that it extends the capability of the model to simulate runoff mechanisms other than infiltration excess. Also, input of parameters for the GSSHA model is significantly different from the methods employed for CASC2D. The current release is GSSHA version 7.0 and is supported by WMS 10.1 (https://www.gsshawiki.com/Gridded_Surface_Subsurface_Hydrologic_Analysis).

Source (Open/Proprietary)

The GSSHA model is coupled with the WMS graphical user interface which is proprietary software from Aquaveo. The WMS Premium edition is required to obtain the GSSHA software and is $6,500 for a user license.

Maintenance

The GSSHA model is developed and maintained by the US Army Engineer Research and Development Center (ERDC) Hydrologic Modeling Branch, in the Coastal and Hydraulics Laboratory. Information on the latest version of the GSSHA model can be found within their wiki ().

For further information regarding the GSSHA model contact Charles Downer (Charles.w.downer@usace.army.mil).

Model Uses

4. Hydrology, nutrient transport, sediment transport, other pollutants?
   Features include two dimensional (2D) overland flow, 1D stream flow, 1D infiltration, 2D groundwater, and full coupling between the groundwater, shallow soils, streams, and overland

flow. Sediment and constituent fate and transport are simulated in the shallow soils, overland flow plane, and in streams and channels. GSSHA can be used as an episodic or continuous model where soil surface moisture, groundwater levels, stream interactions, and constituent fate are continuously simulated.

5. How are SCMs incorporated?
   Hydrologic parameters associated with a grid cell would be manipulated to represent the SCM within a simulation.
6. Duration of Model Run
   Model may be run as a long-term continuous simulation or as a single rain event. Total time of a single event simulation must be set to a value greater than the total rainfall duration plus the expected recession time. For long-term simulations, the total time is determined from the rainfall and hydrometeorological input files.
   a. Minimum/Maximum Time Step
      Typical time steps range from 20 sec to 5 min. One second is the smallest permissible time step. The model time step must be less than and divisible into the smallest increment of time in the rainfall file.

Calibration Method

The model must be manually calibrated and verified to observed discharges at an outlet.

Suggested Tools for Data Entry

The WMS graphical user interface is used for data entry

Watershed Configuration

Land Surface

Area to be simulated: Model Domain

Land unit distribution: Gridded. Distributed model with grid cells ranging from 10 to 1000 m.

Hydrologic unit(s) of land whose topography and drainage system elements direct surface runoff to a single discharge point: Cell

- Minimum/Maximum Unit Size: 10 to 1000 m

Distribution of Impervious/Pervious Land: Individual cell parameters are adjusted to represent impervious/pervious land.

Flow Pathway

Inflow or Discharge Points: As a gridded system, a flow direction map is used to direct overland flow and channel flow. Thus inflow happens in overland cells or channel cells.

Primary flow pathway (channel, pipes, etc.): Nodes and Links.

- A node is a single computational element in the stream network.
- A link is a channel segment comprised of two or more computational nodes.
  - Link types include fluvial, structures, or reservoirs
  - Fluvial links can be either trapezoidal or natural channels represented by breakpoint cross-sections.
    - Trapezoidal cross-section are symmetrical, have constant side slope, and are defined by:
      - Manning’s N
      - Bottom width
      - Channel depth
      - Side slope
    - Breakpoint cross-sections are represented by xy pairs supplied by the user to represent the cross-section
  - Structures are internal boundary conditions within the stream routing network:
    - Horizontal weir
    - Sag Vertical Curve (Parabolic) Weir
    - Circular Culvert
    - Box Culvert
    - Rating Curve
    - Scheduled Release
    - Rule Curve
  - Reservoirs are specified with the LAKE card in the .cif file.

Additional Information

Streams may be classified as either losing or gaining streams by including a STREAM_LOSS CARD. Sediment transport can occur in the channel by identifying links as “ERODE” in the CHAN_INPUT file.

Weather (include time step for applicable fields)
Rain: Precipitation is input by specifying a number of rain gages in the rainfall input file. Precipitation is distributed between the gages using either Thiessen polygons or an inverse distance square weighted method.

Temperature:

Wind Speed:

Relative Humidity:

Solar Radiation:

Forecast data:

Snow: Precipitation is considered to be snow when long-term simulations are conducted and the dry bulb temperature is below 0°C. Snow is treated as a one-layer pack that melts as a result of non-frozen precipitation, net radiation, heat transferred by sublimation and evaporation, and heat transfer as the result of turbulence.

Climate Change:

Surface Runoff and Soil Routing

Inputs/Outputs

Cell inputs = precipitation + overland flow from upstream cell
Cell outputs = infiltration + evapotranspiration + surface runoff

Precipitation

Rain & Snowmelt (defined in the weather section above)

- Interception is modeled using an empirical two-parameter model that accounts for an initial volume of water that vegetation can hold plus the fraction of precipitation captured after the initial volume of water has been satisfied. Rainfall intercepted by vegetation is assumed to evaporate.

Surface Runoff

- Water on the soil surface that neither infiltrates nor evaporates will pond at the surface and can move from grid cell to grid cell as overland flow. Routing is based on a 2-D explicit finite volume solution of the diffusive wave equation. Three solution methods available:
    - Point explicit: Inter-cell fluxes in the *x* and *y* directions, *p* and *q*, respectively, are computed for cell *ij* from depth, d_{ij}, at the N^{th} time level using Manning equation

$$p_{ij}^N = \frac{1}{n}\left(d_{ij}^N\right)^{5/3}\left(S_{fx}^N\right)^{1/2}$$

$$q_{ij}^N = \frac{1}{n}\left(d_{ij}^N\right)^{5/3}\left(S_{fy}^N\right)^{1/2}$$

$$d_{ij}^{N+1} = d_{ij}^N + \frac{\Delta t}{\Delta x}\left(p_{i-1,j}^N + q_{i,j-1}^N - p_{ij}^N - q_{ij}^N\right)$$

    - Alternating Direction Explicit (ADE): Inter-cell flows are first calculated in the *x* direction according to the above equation (*p*). Depths in each row are updated based on the flows in the *x* direction

$$d_{ij}^{N+1/2} = d_{ij}^N + \frac{\Delta t}{\Delta x}\left(p_{i-1,j}^N - p_{ij}^N\right)$$

      Inter-cell flows in the *y* direction are computed using the updated depths

$$q_{ij}^{N+1/2} = \frac{1}{n}\left(d_{ij}^{N+1/2}\right)^{5/3}\left(S_{fy}^{N+1/2}\right)^{1/2}$$

      Depths in each column are updated based on the flows in the *y* direction

$$d_{ij}^{N+1} = d_{ij}^{N+1/2} + \frac{\Delta t}{\Delta x}\left(q_{i,j-1}^{N+1/2} - q_{ij}^{N+1/2}\right)$$

    - ADE with prediction-correction (ADE-PC): All procedures are carried out as in the ADE but additional flows are calculated at the N+1 time step and the flows estimated at the N+1/2 and N+1 time steps are averaged for the time step.
- A depression depth may be specified and no water is routed as overland flow until the depth of water in the cell exceeds the depression depth.
- Fluxes other than inter-cell fluxes (e.g. ET, infiltration, exfiltration) are accounted for before overland routing is computed.

Infiltration

- Green&Ampt: Water is assumed to enter the soil as a sharp (completely saturated) wetting front. Soil assumed to be homogeneous and infinite, with no restrictions due to the water table. Precipitation on dry soil is quickly infiltrated due to capillary pressure. Infiltration decreases as soil becomes saturated until the saturated hydraulic conductivity is reached. Used for single events.
- Multi-layer Green&Ampt: Green&Ampt model assumes infinitely deep, homogeneous, soil column. This GSSHA option allows user to specify three different soil layers.
- Green&Ampt with redistribution: When conducting long-term simulations, multiple sharp wetting fronts can be simulated using this option, and the water is redistributed in the soil column during non-precipitation periods.
- Richards' equation: GSSHA solves 1-D (vertical) head based formulation of Richards' equation:

$$C(\varphi)\frac{\partial\varphi}{\partial t}-\frac{\partial}{\partial z}\left[K(\varphi)\left(\frac{\partial\varphi}{\partial z}-1\right)\right]-W=0$$

    - where:
        - C is specific moisture capacity
        - φ is the soil capillary head
        - z is the vertical coordinate (downward positive)
        - t is time
        - K(φ) is the effective hydraulic conductivity
        - W is a flux term added for sources and sinks
    - Solved using finite difference techniques. Three soil layers, each with independent parameters for each soil type and layer can be specified.

Evapotranspiration

- GSSHA uses ET to track soil moisture conditions for long-term simulations. Potential ET (PET) is calculated by either:
    - Deardorff
    - Penman-Monteith
- Water ponded on the surface of overland cells is reduced up to amount of PET. Any remaining PET demand is applied to cells in the unsaturated zone down to the root depth. Actual ET depends on the PET, water content of soil (θ), wilting point (θ_{wp}), and the field capacity (θ_{fc}):

$$AET=PET\left(\frac{\theta-\theta_{wp}}{\theta_{fc}-\theta_{wp}}\right)^{P}$$

Percolation

NA

Lateral subsurface flow

If Richards' equation is used then lateral subsurface flow is not modeled in the unsaturated zone.

Channel Routing

Routed through a 1-D channel network until it reaches the watershed outlet. Simulated using an explicit diffusive-wave approximation of the St. Venant equations. If you have cells *i-1*, *i*, and *i+1* flowing downstream then inter-cell flows, $Q_{i-1/2}$ and $Q_{i+1/2}$ are computed from depths, *d*, at the *N* time level using the Manning equation:

$$Q_{i+1/2}^{N}=\frac{1}{n}A_i^N(R_i^N)^{2/3}(S_{f_{i+1/2}}^N)^{1/2}$$

where n is the roughness coefficient, A is the area, R is the hydraulic radius, and S_f is the friction slope defined as:

$$S_{f_{i+1/2}}^{N} = S_{o_{i+1/2}} - \frac{d_{i+1}^{N} - d_{i}^{N}}{\Delta x}$$

where S_o is the land surface slope in the x direction. Inter-node fluxes are used to calculate the volume, V, in each node:

$$V_i^{N+1} = V_i^N + \Delta t\left(q_{lat}^{N+1}\Delta x + q_{recharge}^{N+1}\Delta x + Q_{i-1/2}^{N} - Q_{i+1/2}^{N}\right)$$

where q_{lat} is the lateral inflow from the overland flow cells adjacent to the node, $q_{recharge}$ is the exchange between the groundwater and channel. The new volumes are used to compute the node values for A, d, and wetted perimeter at the $N+1$ time step.

Ground Water Routing

Simulation of saturated 2-D groundwater flow by placing GW_SIMULATION card into the project file. Starting water surface elevation must be provided in the WATER_TABLE card. Bedrock elevation specified in the AQUIFER_BOTTOM card. Groundwater time step specified using the GW_TIMESTEP. Meant to be coupled with Richards' equation for infiltration but may be coupled with Green&Ampt with redistribution or Multi-layer Green&Ampt options. The controlling equation is:

$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial x}\left(T_{xy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial y}\left(T_{yx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_{yy}\frac{\partial h}{\partial y}\right) = S\frac{\partial h}{\partial t} + W(x,y,t)$$

where:

- T is the transmissivity
- h is the hydraulic head
- S is the storage term
- W is the flux term for sources and sinks

The equation is solved by successive overrelaxation by lines (LSOR). Maps directly to the overland flow grid. Saturated groundwater zone resides below the unsaturated zone. When simulating saturated groundwater flow, additional processes of stream/channel interaction and exfiltration may occur.

Stream/groundwater interaction

When both saturated groundwater flow and channel routing are being simulated, water flux between the stream and saturated groundwater can be simulated. Cells are considered river flux cells if the overland flow and saturated groundwater flow grid cells. Water will move between the channel and the groundwater based on Darcy's law

Exfiltration

Flux of water from the saturated zone onto the overland flow plane. Occurs when the water table elevation exceeds that of the land surface. Computed using Darcy's law.

Additional Information

Lake and Detention Basin Routing available

Wetland modeling available

Surface inlets and subsurface tile drains can be simulated using the SUPERLINK model. Drains and tiles can discharge to the overland flow plane or the channels. Multiple connected or unconnected networks can be simulated.

APPENDIX C: Hydrologic comparison template for the HP1 model.

Hydrus 1D/PHREEQC (HP1)

General Information

Model History

The models Hydrus 1D and PHREEQ-C were coupled together to create a single model, HP1, that combines the one dimensional water/pollutant transport in unsaturated media from Hydrus 1D with the chemical reactions in equilibrium in soil from PHREEQ-C. Such a model may be useful for introducing constituents from the soil profile that are present in the receiving waters, but are unaccounted for in the source waters. Additional uses include the degradation of organic species, such as PCE, and the long term transient flow and transport of heavy metals, major cations, and other constituents in media with pH dependent cation exchange.

HP1 was developed by the Hydrus 1D developer Jirka Simunek. Version 1.0 was released in November 2004. The current version is 2.2.002, which was released in September 2009. Version 2.3.001 will be released in the near future. The updates in HP1 coincide with updates to each of the separate models.

Source (Open/Proprietary)

Proprietary software, but free.

Maintenance

Jirka Simunek maintains the model for PC-Progress.

Model Uses

7. This model will determine nutrient, heavy metal, and other cation transport in a soil profile. Other pollutant, such as PAHs or pesticides are also possible.
8. How are SCMs incorporated?
   HP1 can simulate SCMs by inserting a pressure head as an upper boundary condition to act as a proxy for pond infiltration.

9. Duration of Model Run
   a. Minimum/Maximum Time Step
      Time can be broken down into 1,000,000 time steps. The time units can be in seconds, minutes, hours, days, or years, however, the minimum recommended time step is 1 sec for large changes in boundary conditions and larger time steps (15 minutes) for long term processes. HP1 automatically selects the optimal time step, so there is no need to constrain the maximum time step.

Calibration Method

HP1 can be run in “Inverse Model” to calibrate against experimental data.

Suggested Tools for Data Entry

Data is entered into HP1 by a GUI. Time variable boundary conditions are entered line by line in the GUI.

Watershed Configuration

HYDRUS-1D is a software package for simulating water, heat, and solute movement in one-dimensional variably saturated media. The model is a network grid of columns and rows with no GIS component, thus no watershed configuration will be outlined.

Land Surface

Area to be simulated: NA

Land unit distribution: Lumped

Hydrologic unit(s) of land whose topography and drainage system elements direct surface runoff to a single discharge point: NA

- Minimum/Maximum Unit Size: NA

Distribution of Impervious/Pervious Land: NA

Flow Pathway

Inflow or Discharge Points: Node

- A matrix of nodes is setup to represent the soil media.

Primary flow pathway (channel, pipes, etc.): NA

Additional Information

NA

Weather (include time step for applicable fields)
Parameters except Rain are turned on in the Meteorological Parameters

Rain: Supplied by user in spreadsheet form

Temperature: Supplied by user as a time series of point values containing daily min/max.

Wind Speed: Supplied by user as a time series of average daily wind speed.

Relative Humidity: Supplied by user as a time series (or vapor pressure).

Solar Radiation: Supplied by user as a time series (or net radiation).

SunHours: Supplied by user as a time series.

Forecast data: NA

Snow: Supplied by user as a time series (precipitation is assumed to be in the form of snow when temperature is below -2℃, form of liquid when air temperature is above +2℃, and a linear transition exists between these two limiting temperatures)

Climate Change: NA

- Can enter in different scenarios but not built in climate change

Surface Runoff and Soil Routing

Inputs/Outputs

Node inputs = precipitation (if top layer) or movement from upstream nodes

Node outputs = infiltration + evapotranspiration + surface runoff (if top layer) + movement of water to more downstream nodes (downward if vertical model)

Precipitation

Rain & Snowmelt (defined in the weather section above)

- Canopy storage can intercept and store precipitation calculated from leaf area index

Surface Runoff

- Water can pond at the surface of the soil through atmospheric boundary conditions. The height of the surface water layer increases due to precipitation and reduces because of infiltration and evaporation.

Infiltration

HYDRUS-1D has several options for calculating water movement through media. For uniform movement a modified version of the Richards equation using the assumptions that the air phase plays insignificant role in the liquid flow process and that water flow due to thermal gradients can be neglected is used:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K\left(\frac{\partial h}{\partial x} + \cos \alpha\right)\right] - S$$

- h is the water pressure head
- θ is the volumetric water content
- t is time
- x is the spatial coordinate
- S is the sink term. Volume of water removed from a unit volume of soil per unit time due to plant water uptake.
- α is the angle between the flow direction and the vertical axis
- K is the unsaturated hydraulic conductivity

Modifications are available in HYDRUS-1D for uniform water flow with vapor transport (may be significant given we are in a semiarid climate), flow in dual-porosity systems (flow is restricted to fractures and water in the matrix does not move), flow in dual-permeability systems (flow through both fractures and the soil matrix).

HYDRUS permits the use of different analytical methods for the hydraulic properties (soil water retention and hydraulic conductivity):

- Brooks and Corey
- van Genuchten-Muslem
- Modified van Genuchten
- Kosugi (log-normal)
- Dumer, dual van Genuchten-Muselm (for dual-porosity systems)
- Gerke and van Genuchten (dual-permeability)

Hydrus also allows for several options for hysteresis.

Evapotranspiration

Potential ET may be calculated using Penman-Monteith or Hargreaves equation.

Root water uptake is modeled using water stress response models Feddes or S-shaped (van Genuchten)

Percolation

No percolation modeled.

Lateral subsurface flow

Lateral flow through the soil could be modeled with similar descriptions in the Infiltration section above if the angle of the water flow was adjusted.

Channel Routing

No streams in this model.

Ground Water Routing

No ground water modeling.

Additional Information

No additional information

APPENDIX D: Hydrologic comparison template for HSPF.

Hydrological Simulation Program – Fortran (HSPF)

General Information

Model History

The HSPF model was first released to the public in 1980; however, the history of the model dates back to the around the 1960s. In the early 1960s, Ray Linsley and Norman Crawford developed the Stanford Watershed Model, which was designed to model hydrologic processes continuously in time with smaller than daily time steps. Crawford worked on the computer program as part of his Ph.D work to expand a basic water balance he and Linsley had created for Los Trancos Creek, a San Francisquito Creek tributary. In the 1970s, nonpoint source loading and water quality simulation processes were added to the Stanford Watershed Model and the program was renamed the Hydrocomp Simulation Program (HSP).

In addition, the EPA sponsored the Agricultural Runoff Management (ARM) model and Nonpoint Source (NPS) pollutant loading models to address pollution in the early 1970s. By the late 1970s, the EPA funded the development of HSPF which incorporated all the functions of the HSP, ARM, and NPS models but was easier to maintain.

Source (Open/Proprietary)

Open source

Maintenance

The US EPA and USGS jointly sponsor HSPF but AQUA TERRA Consultants is the EPA maintenance contractor. All code changes and new releases have been performed by AQUA TERRA in conjunction with the EPA Athens Laboratory and the USGS Office of Surface Water.

Model Uses

10. Hydrology, nutrient transport, sediment transport, other pollutants?
    Flood control planning and operations, River basin and watershed planning, Storm drain analyses, Water quality planning and management, Point and nonpoint source pollution analyses, Soil erosion and sediment transport, Evaluation of best management practices, Fate and transport of pesticides, nutrients, and toxic substances
11. How are SCMs incorporated?
    HSPF incorporates a BMP Toolkit that allows for the simulation of storage and infiltration SCMs
12. Duration of Model Run
    Periods can be as short as a few minutes to over 100 years. The model is better designed for long-term simulation. While time steps are small enough to simulate single storm events, the over-land area is a leveled detention storage and may be inadequate for simulating intense single storm events especially over large drainage areas.
    a. Minimum/Maximum Time Step
       Time steps range from 1 minute to 1 day

Calibration Method

Manal calibration. HSPF-SCE is an automated calibration tool developed using the R software.

Suggested Tools for Data Entry

The EPA has suggested BASINS as the tool for building HSPF models. The Watershed Modeling System (WMS) can also be used to build HSPF models.

Watershed Configuration

Land Surface

Area to be simulated: Watershed

Land unit distribution: Lumped

Hydrologic unit(s) of land whose topography and drainage system elements direct surface runoff to a single discharge point: Land Segment

- Minimum/Maximum Unit Size: NA

Distribution of Impervious/Pervious Land:

- Land Segments can either be pervious or impervious
- The PERLND module is used to simulate water quality and quantity on pervious land segments
- The IMPLND module is used to simulate water quality and quantity on impervious land segments

Flow Pathway

Inflow or Discharge Points: Water and other constituents from an upstream reach (RCHRES) and local sources enter a reach through a single INFLO. Outflow from a RCHRES may leave through one of five exits (OFLO). Precipitation, evaporation, and other fluxes may influence the processes which occur in the RCHRES, but do not pass through the exits.

Primary flow pathway (channel, pipes, etc.): Reaches.

- The RCHRES module simulates processes which occur in a single reach of open or closed channel or a completely mixed lake.
- The RCHRES consists of a single zone situated between two nodes.

Additional Information

Weather (include time step for applicable fields)
Meteorologic data is input as time series into the EXTNL group

Rain: Measured precipitation (PREC)

Air Temperature: Measured air temperature (GATMP)

Wind Speed: Measured wind movement (WINMOV)

Relative Humidity: Measured dewpoint temperature (DTMPG)

Solar Radiation: Measured solar radiation (SOLRAD)

Forecast data: NA

Snow: The SNOW module deals with runoff derived from the fall, accumulation, and melt of snow. Two options exist in HSPF for handling snow.

- The first is based on work by the Corps of Engineers which uses meteorologic data to determine whether precipitation is rain or snow and simulates heat fluxes on snowpacks
- The second uses a temperature index, or degree-day, approach. Most processes are similar to the first option but the snowmelt due to atmospheric heat exchange is calculated using the air temperature and an empirical degree-day factor

Climate Change: NA

Additional Information
Cloud cover is an optional input for meterologic data entry (CLOUD)
Input potential ET (PETINP)
Input irrigation demand (IRRINP)
Under the IMPLND module the user can also input Solar radiation: total for 1 day (DSOLAR)

Surface Runoff and Soil Routing

Inputs/Outputs

For pervious Land Segments

1. Moisture (rain or snow) enters the interception storage.
2. Overflow from the interception storage is added to a supplied time series of external lateral inflow (optional) to create the total inflow into the surface detention storage.
3. Inflow to the surface detention storage is added to existing storage to make up water available for infiltration and runoff from the surface detention storage.
4. Moisture leaves the surface detention storage via surface runoff (see *Surface Runoff* below), entering the interflow storage (see *Lateral subsurface flow* below), entering the upper zone storage (see *Infiltration* below), or directly infiltrating to the lower zone and groundwater storages (see *Infiltration* below). Water does not have to leave and can remain in the surface detention storage.
5. Moisture traveling laterally through the soil leaves the interflow storage.
6. Moisture in the upper zone can percolate to the lower zone and groundwater storages or be lost to ET (see *Percolation* below).
7. Moisture from direct infiltration and percolation from the upper zone can enter the lower zone storage, active groundwater storage, or experience deep percolation (this water is lost in the simulation).
8. Moisture leaves the lower zone storage via ET.
9. Moisture leaves the active groundwater storage via ET or groundwater outflow to a channel.

For impervious Land Segments

1. Moisture (rain or snow) enters impervious retention storage.
2. Later surface flow can also enter the impervious retention storage if the user selects the option RTLIFG=1.
3. The user may assign a retention capacity, RETSC, which will designate any retention of moisture which does not reach the overland flow plane (roof top catchment, asphalt wetting, improper drainage, etc.)
4. Water is removed from retention storage by evaporation, determined in the EVRETN subroutine.
5. Moisture exceeding the retention capacity overflows the retention storage and moves to the surface detention storage.
6. Lateral surface flow can skip the impervious retention storage and enter the surface detention storage if the user selects the option RTLIFG=0.
7. Existing water in the surface detention plus any inflow to the surface detention storage is considered the moisture supply.
8. The moisture supply is routed as runoff in the IROUTE subroutine.

Precipitation (subroutine SUPY)

Interception is handled in the ICEPT subroutine. The user supplies the interception capacity on a monthly basis to account for seasonal variation or may supply one value as a fixed capacity. Moisture exceeding the interception capacity overflows the interception storage and is ready for infiltration or runoff. Water held in interception storage is removed by evaporation, which is determined in the EVICEP subroutine.

Surface Runoff (subroutines PROUTE, IROUTE)

Simulated using the Chezy-Manning equation and an empirical expression which relates outflow depth to detention storage. Rate of overland flow discharge is determined by the equations:

If SURSM (mean surface detention storage over the time interval) < SURSE (equilibrium surface detention storage for current supply rate) [overland flow rate is increasing]

$$SURO = DELT60 * SRC * (SURSM * (1.0 + 0.6\left(\frac{SURSM}{SURSE}\right)^3)^{1.67}$$

If SURSM ≥ SURSE [overland flow rate is at equilibrium or decreasing]

$$SURO = DELT60 * SRC * (SURSM * 1.6)^{1.67}$$

- SURO = surface outflow
- DETL60 = DELT/60
- SRC = routing variable, calculated daily in SURFAC subroutine

$$SRC = 1020.0 * \frac{\sqrt{SLSUR}}{NSUR * LSUR}$$

  - NSUR = Manning's n for the overland flow plane (can be input on monthly basis)
  - LSUR = length of the overland flow plane
  - SLSUR = slope of the overland flow plane

$$SURSE = DEC * SSUPR^{0.6}$$

  - DEC = calculated routing variable, calculated daily in SURFAC subroutine

$$DEC = 0.00982 * (\frac{NSUR * LSUR}{\sqrt{SLSUR}})^{0.6}$$

  - SSUPR = rate of moisture supply to overland flow surface

Two options to estimate SURSM and SSUPR

1. SSUPR = PSUR – SURS and SURSM = mean(SURS,PSUR)
2. SSUPR = (PSUR – SURS)/DELT60 and SURSM = SURS
   - PSUR = potential surface detention determined in DISPOS subroutine
   - SURS = surface storage at the start of the interval

Infiltration

Moisture available to the land surface (MSUPY) is distributed to one of four fates:

- Infiltration
- Upper zone storage or interflow storage
- Run off
- Remain in surface detention storage

The distribution of the moisture is best represented in Figure 1. Moisture below the infiltration capacity (line I) will go to infiltration, while moisture above the infiltration capacity but below MSUPY is designated as the potential direct runoff (PDRO). The PDRO will go to upper zone or interflow storages, run off, or remain in surface detention. Moisture that is designated PDRO but falls below line II is called potential interflow inflow and will go to the upper zone or interflow storages. Moisture that is designated PDRO but falls above line II is called potential surface detention/runoff and will available for run off, surface detention storage, or further upper zone storage.

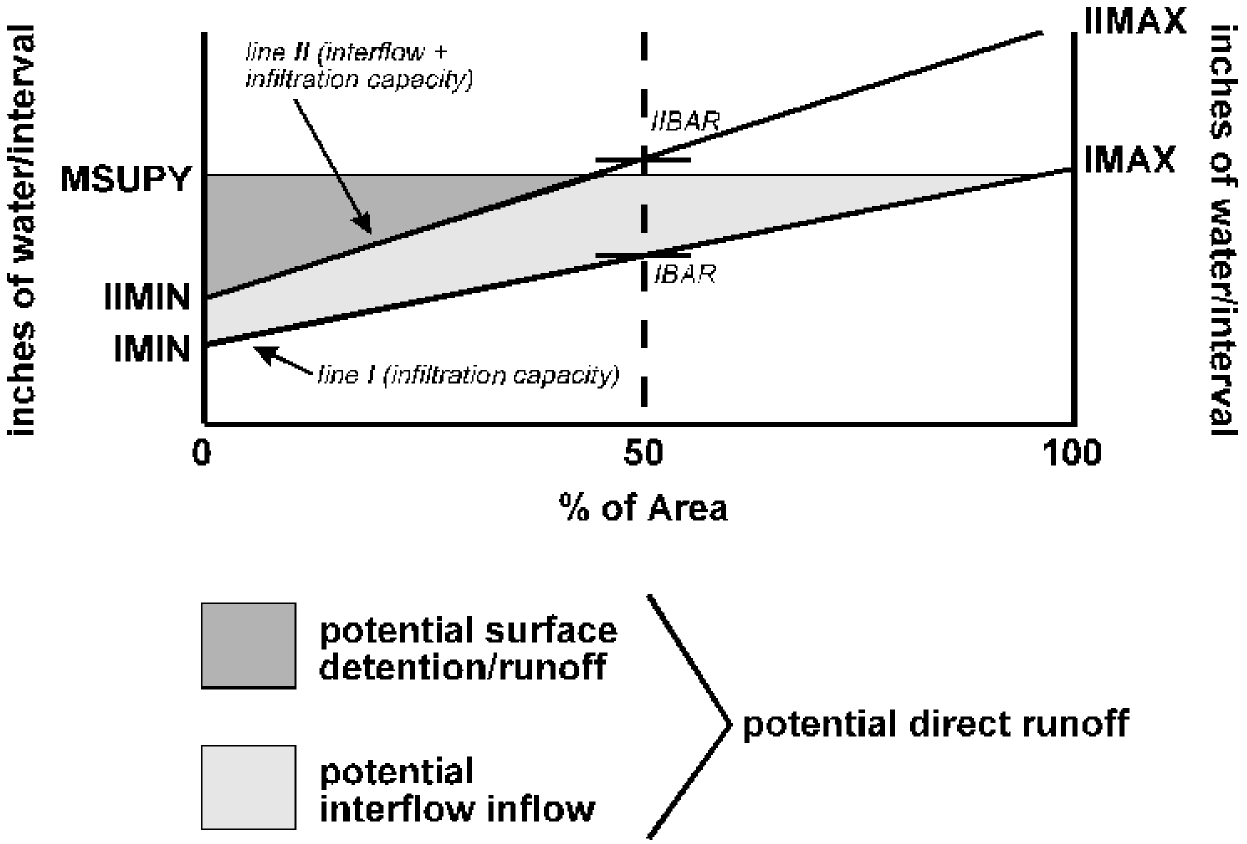


Figure 1: Determination of infiltration, potential interflow, and potential surface detention/runoff.

The subroutine SURFAC is used to determine the location of lines I and II:

$$IBAR = \left(\frac{INFILT}{(LZS/LZSN)^{INFEXP}}\right) * INFFAC$$

$$IMAX = INFILD * IBAR$$

$$IMIN = IBAR - (IMAX - IBAR)$$

$$RATIO = INTFW * \left(2^{LZS/LZSN}\right)$$

where:

- IBAR is the mean infiltration capacity over the land segment
- INFILT is the infiltration parameter
- LZS is the lower zone storage
- LZSN is the parameter for lower zone nominal storage
- INFEXP is the exponent parameter greater than one
- INFFAC is the factor to account for frozen ground effects, if applicable
- IMAX is the maximum infiltration capacity
- INFILD is the parameter giving the ratio of maximum to mean infiltration capacity over the land segment
- IMIN is the minimum infiltration capacity
- RATIO is the ratio of the ordinates of line II to line I

- INTFW is the interflow inflow parameter

The amount of PDRO which travels to the upper zone storage is calculated in the subroutine UZINF. The equations used to define the relationship follow:

$$FRAC = 1 - \left(\frac{UZRAT}{2}\right) * \left(\frac{1}{4 - UZRAT}\right)^{3-UZRAT} \qquad for\ UZRAT \leq 2$$

$$FRAC = \left(\frac{0.5}{UZRAT - 1}\right)^{2*UZRAT-3} \qquad for\ UZRAT > 2$$

where:
- FRAC is the fraction of PDRO retained by the upper zone storage
- UZRAT is the UZS/UZSN (ratio of the storage to the nominal capacity)

It can be beneficial to integrate over the interval to find inflow to the upper zone when using large time steps since UZS and FRAC are dynamically affected by the inflow process. The subroutine UZINF1 considers the following differential equation:

$$\frac{d(UZS)}{dt} = \frac{d(UZRAT)}{dt} * UZSN = PDRO * FRAC$$

Thus

$$\frac{d(UZRAT)}{FRAC} = \left(\frac{PDRO}{UZSN}\right) dt$$

And taking the integral of the equation:

$$INTGRL = \int_{UZRATt1}^{UZRATt2} \frac{d(UZRAT)}{FRAC} = \left(\frac{PDRO}{UZSN}\right)(t2 - t1)$$

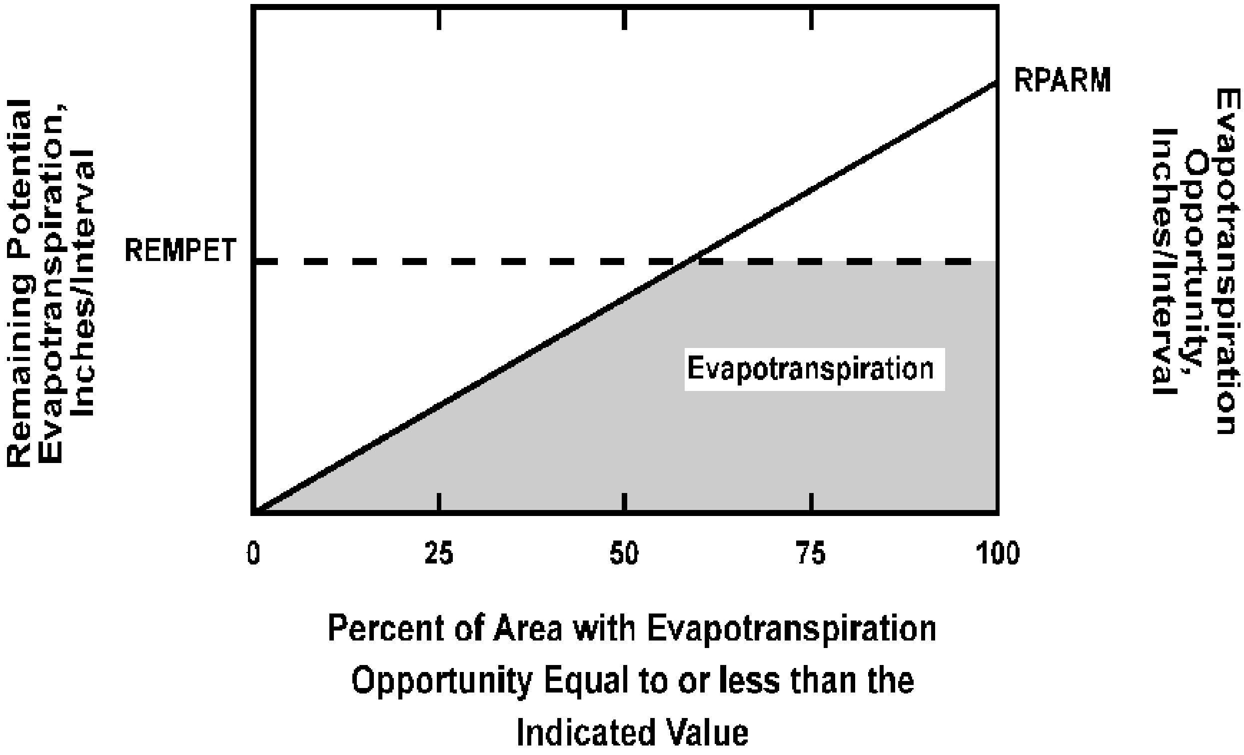
where:
- t1 is the time at the start of the interval
- t2 is the time at the end of the interval

Subroutine UZINF1 uses tabulated corresponding values of INTGRL and UZRAT to evaluate the above, which enables the program to find the change in UZRAT over the interval and hence the quantity of inflow. A second alternative subroutine, UZINF2, will use the UZRAT at the start of the simulation interval for the entire time step to calculate the inflow.

Evapotranspiration (subroutine EVAPT)
Simulate ET fluxes from all zones of the pervious land segment. Potential ET is supplied as an input time series, typically using U.S. Weather Bureau Class A pan records plus an adjustment factor. Data are further adjusted for cover in the PWATER subroutine. Actual ET is then calculated by a function of moisture storages and the potential. There are 5 sources for ET to come from:

- First source is the active groundwater outflow or baseflow. This simulates riparian vegetation ET as groundwater enters the stream. User may specify the fraction of the potential ET that can be sought from the baseflow in BASETP. Remaining potential ET not met by baseflow ET will try next to be satisfied in EVICEP subroutine

- The next water in question is in the interception storage. There is no parameter regulating the rate of ET from interception storage. Demand will draw upon all of the interception storage unless the demand is less than the storage. When demand is greater than the storage, the next subroutine to be taxed is the ETUZON
- The next water in question is in the upper zone. ET is based on the moisture in storage in relation to its nominal capacity. ET will occur from the upper zone storage at the remaining potential demand if the ratio of upper zone storage to nominal capacity (UZS/UZSN) is greater than 2.0. Otherwise, potential ET demand is reduced; the adjusted value depends on the UZS/UZSN ratio. Next subroutine taxed is the ETAGW
- The next water in question is in the active groundwater. Within the subroutine ETAGW the parameter AGWETP is the fraction of the remaining potential ET that can be sought from the active groundwater storage. Can be met only if there is enough active groundwater storage to satisfy it. Next subroutine taxed is the ETLZON.
- The last storage taxed is the lower zone. ET from the lower zone depends upon vegetation transpiration and will vary with the vegetation type, depth of rooting, density of vegetation cover, and stage of plant growth along with the moisture characteristics of the soil zone. These are lumped into the LZETP parameter which can be input on a monthly basis to account for temporal change. Usually vegetation type and/or rooting depth will vary over the land segment. A linear probability density function for ET opportunity is assumed to simulate this. The quantity of water lost by ET from the lower zone when the remaining potential ET (REMPET) is less than RPARM, is given by the cross-hatched area of the figure below. When REMPET is more than RPARM the lower zone ET is equal to the entire area under the triangle, RPARM/2:



$$RPARM = \frac{0.25}{1.0 - LZETP} * (\frac{LZS}{LZSN}) * \frac{DELT60}{24.0}$$

  - RPARM = maximum ET opportunity
  - LZETP = lower zone ET parameter
  - LZS = current lower zone storage
  - LZSN = lower zone nominal storage parameter
  - DELT60 = hr/interval

ET from the lower zone is further reduced when LZETP is less than 0.5 by multiplying LZETP by 2.0. Designed to account for the fraction of the land segment devoid of any vegetation that can draw from the lower zone. Further options are available if HSPF is linked with MODFLOW.

Percolation

Upper zone inflow calculated in DISPOS, plus lateral inflow and/or irrigation is first added to the upper zone storage at the start of the interval to obtain the total water available for percolation from the upper zone. Percolation only occurs when UZRAT minus LZRAT is greater than 0.01 and is calculated as:

$$PERC = 0.1 * INFILT * INFFAC * UZSN * (UZRAT - LZRAT)^3$$

where:

- PERC is the percolation from the upper zone
- INFILT is the infiltration parameter
- UZSN is the parameter for upper zone nominal storage
- UZRAT is the ratio of upper storage to UZSN
- LZRAT is the ratio of lower zone storage to lower zone nominal storage

Lateral subsurface flow

The amount of moisture that enters the interflow storage is moisture that is designated potential interflow inflow plus lateral interflow from upstream land segments minus the moisture that enters the upper zone storage. The calculation of interflow outflow (or lateral interflow) is handled in the INTFLW subroutine and is calculated as follows:

$$IFWO = IFWK1 * INFLO + IFWK2 * IFWS$$

where:

- IFWO is the interflow outflow
- INFLO is the inflow into interflow storage, including later inflow
- IFWS is the interflow storage at the start of the interval
- IFWK1 and IFWK2 are determine by the following:

$$IFWK1 = 1.0 - \frac{IFWK2}{KIFW}$$
$$IFWK2 = 1.0 - \exp(-KIFW)$$

And

$$KIFW = -ALOG(IRC) * \frac{DELT60}{24.0}$$

where:

- IRC is the interflow recession parameter
- DELT60 is the number of hours per interval
- 24.0 is the number of hours per day
- exp is the exponential function
- ALOG is the natural logarithm function

Channel Routing

The subroutine HYDR simulates the hydraulic processes occurring in the RCHRES. Water entering the RCHRES from all surface and subsurface sources goes through a "gate" called INFLO. The quantity of water is called IVOL. The user indicates the time series which enter this gate in the EXT SOURCES or NETWORK Block in the User's Control Input (UCI), otherwise the system assumes the RCHRES has zero inflow. The user may also indicate precipitation and evaporation acting directly on water in the RCHRES by supplying time series PREC and/or POTEV in the UCI (EXT SOURCES block). The equation for the volume of water in the RCHRES is as follows:

$$VOL - VOLS = IVOL + PRSUPY - VOLEV - ROVOL$$

where:

- VOL is the volume at the end of the interval
- VOLS is the volume at the start of the interval
- PRSUPY is the volume of precipitation calculated from the PREC time series
- VOLEV is the volume of evaporation calculated from the POTEV time series
- ROVOL is the total outflow volume

The primary goal of the subroutine is to estimate ROVOL which is assumed to be a weighted mean of the rates at the start and end of the interval:

$$ROVOL = (KS * ROS + COKS * ROD) * DELTS$$

where:

- KS is a weighting factor (0 ≤ KS ≤ 0.99), supplied by user or default
- COKS = 1.0 - KS
- ROS is the total rate of outflow from the RCHRES at the start of the interval
- ROD is the total rate of demanded outflow for the end of the interval
- DELTS is the simulation interval in seconds

The equation for VOL can then be written as:

$$VOL = VOLT - (KS * ROS + COKS * ROD) * DELTS \quad Eq. 1$$

where

$$VOLT = IVOL + PRSUPY - VOLEV + VOLS$$

The two parameters to be solved are VOL and ROD. In HSPF it is assumed that there may be up to 5 exits for water from the RCHRES and each exit has an outflow demand that is a function of volume or time or a combination of the two:

$$OD(1) = f1(VOL, t)$$
$$\ldots$$
$$OD(NEXITS) = fNEXITS(VOL, t)$$

Thus the total outflow demand is also a function of volume or time or a combination:

$$ROD = funct(VOL, t)$$

At a given time in the simulation, t is known and the above functions can be reduced to:

$$OD(N) = fN(VOL) \quad Eq. 2$$
$$ROD = funct(VOL) \quad Eq. 3$$

The point of intersection of equations 1 and 3 gives the values RO (the total rate of outflow from the RCHRES at the end of the interval), VOL, and O(N) [rate of outflow through exit N at the end of the interval]. To find this intersection HSPF uses several methods:

- If at least one OD(N) is a function of volume then HSPF uses the subroutine ROUTE to solve for VOL and ROD.
- If no OD(N) is a function of volume, only functions of time, then HSPF uses the NOROUT subroutine to solve for VOL and ROD.

To use the ROUTE subroutine the user must specify properties of a RCHRES in a table called RCHTAB which includes information on depth, surface area, volume, and volume dependent functions of that RCHRES. Equations 2 and 3 are represented by a series of straight line segments. A segment of equation 3 can be represented by the following:

$$\frac{VOL - V1}{ROD - ROD1} = \frac{V2 - V1}{ROD2 - ROD1} \quad Eq. 4$$

where V1 and V2 are volumes specified in adjacent rows of RCHTAB and ROD1 and ROD2 are the corresponding total outflow demands.

HSPF first attempts to find the intercept to equation 1 on the volume axis:

$$VOLINT = VOLT - KS * ROS * DELTS$$

- If VOLINT is less than zero, the equations cannot be solved and HSPF does the following:
    - VOL = 0.0
    - RO = 0.0
    - O(N) = 0.0
    - ROVOL = VOLT
- If VOLINT is greater than or equal to zero:
    - The intercept of equation 1 on the volume axis is found

      $$OINT = \frac{VOLINT}{DELTS * COKS}$$
    - The maximum outflow demand for which the volume is still zero (RODZ) is found.
    - If OINT > RODZ then equations can be solved through SOLVE subroutine
    - If OINT ≤ RODZ then equations cannot be solved. The code assigns a zero value to the RCHRES volume and the total outflow is equal to the OINT.

The approach that is taken in subroutine SOLVE selects a segment of equation 3 and determines the point of intersection with equation 1. If the intersection lies outside the selected segment, the code selects adjacent segments until the intersection lies within the selected segment. Equations 1 and 4, respectively, can be written as follows:

$$A1 * VOL + B1 * ROD = C1$$
$$A2 * VOL + B2 * ROD = C2$$

where:

- A1 = 1.0 / (COKS*DELTS)
- A2 = ROD1 – ROD2
- B1 = 1.0
- B2 = V2 – V1
- C1 = OINT
- C2 = (V2*ROD1) – (V1*ROD2)

Then the equations can be solved by evaluating the determinants:

$$DET = A1 * B2 - A2$$
$$DETV = OINT * B2 - C2$$
$$DETO = A1 * C2 - A2 * OINT$$

And the points of intersection are:

$$VOL = DETV/DET$$

$$RO = DETO/DET$$

The solution procedure in the NOROUT subroutine is similar to the method used in the ROUTE subroutine except no table look-up or interpolation is required. The intercept of equation 1 on the volume axis is found as above.

- If VOLINT < 0.0, there is no solution and the code takes similar action to that taken by subroutine ROUTE.
- If VOLINT ≥ 0.0:
  - OINT is calculated as above.
  - If OINT > ROD then
    - RO = ROD
    - O(N) = OD(N)
    - VOL = VOLINT – COKS*RO*DELTS
  - If OINT ≤ ROD then equations cannot be solved. The code assigns a zero value to the RCHRES volume and the total outflow is equal to the OINT.

Ground Water Routing

Inflow to the inactive or active groundwater is the quantity of direct infiltration plus percolation from the upper zone plus lateral inflow from the lower zone (this is what the manual says but I cannot find any equations showing lateral flow from the lower zone) which does not go to the lower zone. The fraction that goes to the lower zone is computed in the subroutine LZONE:

$$LZFRAC = 1.0 - LZRAT * \left(\frac{1}{1 + INDX}\right)^{INDX} \quad when\, LZRAT < 1.0$$

$$LZFRAC = \left(\frac{1}{1 + INDX}\right)^{INDX} \quad when\ LZRAT > 1.0$$

$$INDX = 1.5 * ABS(LZRAT - 1.0) + 1.0$$

where:

- LZFRAC is the fraction of infiltration plus percolation plus lower zone lateral inflow that enters LZS
- LZRAT is LZS/LZSN
- ABS is the function for determining absolute value

The distribution to inactive or active groundwater is designated by the user as the DEEPFR parameter, which is the fraction of the groundwater inflow which goes to inactive groundwater. The remaining portion plus all lateral groundwater flow and/or irrigation application make up the total inflow to the active groundwater storage.

Outflow from the active groundwater storage is calculated as:

$$AGWO = KGW * (1.0 + KVARY * GWVS) * AGWS$$

where:

- AGWO is the active groundwater outflow
- KGW is the groundwater outflow recession parameter
- KVARY is a parameter which can make active groundwater storage to outflow relation nonlinear
- GWVS is the index to groundwater slope
- AGWS is the active groundwater storage at the start of the interval

The parameter KGW is calculated using the relationship:

$$KGW = 1.0 - AGWRC^{DELT60/24}$$

Where:

- AGWRC is the daily recession constant of groundwater flow if KVARY or GWVS = 0.0; i.e., the ratio of current groundwater discharge to groundwater discharge 24-hr earlier
- DELT60 is hr/interval

Additional Information

APPENDIX E: Hydrologic comparison template for MODFLOW 6.

MODFLOW

General Information

Model History

Developed by the US Geological Survey (USGS) as a three-dimensional finite-difference groundwater model first published in 1984. The model was originally built solely for groundwater-flow simulations; however, the USGS has added modules to MODFLOW that have expanded the capabilities to include groundwater and surface water interactions, solute transport, flow through soil unsaturated zones, and groundwater management. The current release is MODFLOW 6 and a full list of modules related to MODFLOW can be found at the USGS website (https://water.usgs.gov/ogw/modflow/).

Source (Open/Proprietary)

Open source

Maintenance

US Geological Survey

Limited support is provided by emailing modflow@usgs.gov or by contacting Chris Langevin, Joe Hughes, or Ned Banta within the Earth Systems Modeling Branch, Integrated Modeling and Prediction Division, Water Mission Area, US Geological Survey

Model Uses

13. Hydrology for surface and groundwater interactions, flow through unsaturated and saturated soil, flow through aquifers. Additional programs related to MODFLOW exist for solute transport.
14. How are SCMs incorporated?
    Manipulation of flow and transport parameters for grid cells at the land surface of the model.
15. Duration of Model Run
    Long-term or single event.
    a. Minimum/Maximum Time Step
       Undocumented but time units listed within the model are seconds, minutes, hours, days, or years.

Calibration Method

Autocalibration of flow may be done using the Parameter Estimation Model Wrapper MODFLOW/PEST

Suggested Tools for Data Entry

Many exist but common utilities include FloPy v.3.2.9, ModelMuse, MFI, MODFLOW-GUI.

Watershed Configuration

Land Surface

Area to be simulated: Domain

Land unit distribution: Gridded. MODFLOW is a gridded system which can be spatially setup in the either the structured Discretization (DIS) Package, Discretization by Vertices (DISV) Package, or the Unstructured Discretization (DISU) Package. The DIS Package is the traditional setup where cells are identified by their layer, row, and column position within a 3D grid. In the DISV Package, the user must enter x,y pairs for each cell. In the DISU Package the user must specify all cell information and information about how cells are connected.

Hydrologic unit(s) of land whose topography and drainage system elements direct surface runoff to a single discharge point: Cell

- Minimum/Maximum Unit Size: Undocumented

Distribution of Impervious/Pervious Land: Manipulation of infiltration parameters for cells in the surface water/groundwater interaction row of the grid

Flow Pathway

Inflow or Discharge Points: Inflow is primarily from precipitation and happens at the top most layer of cells designated by the user.

Primary flow pathway (channel, pipes, etc.): Cells are connected in the selected discretization package and flow passes between cells based on boundary conditions and flow equations described in the below sections.

Additional Information

Open-source groundwater flow model distributed by the USGS. Current version is MODFLOW 6 which is a framework to solve multiple, tightly coupled, numerical models in a single system of equations. Variants include but are not limited to:

- GSFLOW couples PRMS hydrologic model with MODFLOW
- MODFLOW-CFP includes the Conduit Flow Process (CFP) developed to simulate non-Darcian flow in karst aquifers
- MODFLOW-GWM which optimizes groundwater management strategies
- MODFLOW-SWR includes a surface-water model for simulating coupled groundwater and surface-water interactions
- MODFLOW-LGR allows multiple groundwater flow models to be coupled within a local grid refinement
- MODFLOW-USG is an unstructured grid version of MODFLOW that allows flexible grid geometries

This template will not include these variants and will only cover the base MODFLOW 6 version.

Weather (include time step for applicable fields)
Rain: The recharge flux is inserted as a time series into the PERIOD block.

Temperature:

Evaporation:

Wind Speed:

Snowmelt:

Climate Change:

Surface Runoff and Soil Routing

Inputs/Outputs

Inputs and Outputs to cells are complicated and are discussed in detail in the sections below.

Precipitation

Rain (defined in the weather section above)

Surface Runoff

The Water Mover (MVR) Package can be used to simulate some surface runoff. Rejected infiltration rates and exfiltration rates from the UZF Package may be added to the MVR Package and then the MVR Package can add water into either the SFR package if connecting to a stream cell or the UZF Package if connecting to an overland cell.

Infiltration

Recharge (RCH) Package which maps water directly to a groundwater layer.

The Recharge (RCH) Package is designed to simulate recharge to the groundwater system:

$$QR_{nb} = I_{nb} M_{nb} A_n$$

- QR_{nb} is the recharge flow rate applied to cell n
- I_{nb} is the recharge flux applicable to the map area, A_n, of the cell
- M_{nb} is an area multiplier that can be used to scale I_{nb} (e.g., to account for impervious areas in a cell)

Two options for recharge: 1) apply recharge to the highest active cell 2) recharge will be applied to the cell specified by the user. If that cell is dry, then recharge to that cell will be lost in option 2, because it is not routed down to an active cell beneath it.

Unsaturated Zone Flow (UZF) Package which maps water to the groundwater through an unsaturated soil layer.

Unsaturated Zone

The UZF package does not account for capillary-induced infiltration at the onset of wetting when negative pressure gradients can be large relative to gravity potential gradients and likely under predicts the infiltration and advancement of the wetting front within hours of the onset of the infiltration event. However, capillary pressure gradients subside quickly and gravity quickly becomes dominant. Negative pressure gradients also may result in lateral and vertical redistribution in the unsaturated zone, which is not simulated by the UZF package. The model likely results in errors in simulated infiltration when the rainfall rate is greater than the saturated vertical hydraulic conductivity and stress periods less than 1 day are used.

The UZF package approximates vertical flow through a homogeneous unsaturated zone by using a simplified version of the Richards equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial q_{UZF}}{\partial z} - i_{ET} = \frac{\partial}{\partial z}\left[D(\theta)\frac{\partial \theta}{\partial z} - K(\theta)\right] - i_{ET}$$

- where:
    - θ is the volumetric water content
    - q_{UZF} is the vertical water flux in the unsaturated zone
    - $D(\theta)$ is the hydraulic diffusivity

- $K(\theta)$ is the vertical unsaturated hydraulic conductivity as a function of water content
- i_{ET} is the unsaturated zone ET rate per unit depth

The diffusive term is stripped out and yields vertical flux depending on gravity and ET:

$$\frac{\partial\theta}{\partial t}+\frac{\partial K(\theta)}{\partial z}+i_{ET}=0$$

Which is solved using two ordinary differential equations representing the velocity of a wetting or drying wave and the change in the water content due to ET:

$$\frac{dz}{dt}=\frac{\partial K(\theta)}{\partial\theta}=v(\theta)$$

$$\frac{d\theta}{dt}=-i_{ET}$$

Integrating the above equations results in:

$$v_1=\frac{K(\theta_{t1})-K(\theta_{t0})}{\theta_{t1}-\theta_{t0}}$$

where v_1 is the current wave velocity, θ_{t1} is the current volumetric water content of a wave moving through sediment, and θ_{t0} is the initial water content of a wave moving through sediment. Water content along the wetting or drying profile is calculated as:

$$\theta_{t+\Delta t}=-i_{ET}\theta_t\Delta t$$

where $\theta_{t+\Delta t}$ is the current water content along the wetting or drying profile at time $t+\Delta t$ and θ_t is the previous water content along the wetting or drying profile at time t. The Brooks-Corey unsaturated hydraulic conductivity function can be used to evaluate $K(\theta)$ and can be expressed as:

$$K(\theta)=K_{sat}\left[\frac{\theta-\theta_{resid}}{\theta_{sat}-\theta_{resid}}\right]^{\varepsilon}$$

where K_{sat} is the saturated hydraulic conductivity, θ_{resid} is the residual (irreducible) water content, θ_{sat} is the saturated water content, ε and is the Brooks-Corey exponent.

Evapotranspiration

The ET package simulates the effects of transpiration and evaporation in removing water from the saturated groundwater while the UZF package can be used for the unsaturated zone and saturated zone if an unsaturated zone is simulated.

Evapotranspiration (ET) Package

When the water table is at or above a specified elevation, $SURF_{nb}$, ET loss from the water table occurs at a fixed rate specified by the user. Or the rate of loss per unit surface area of water table due to ET (RET_{nb}) is equal to a defined maximum possible value of RET ($EVTR_{nb}$):

$$RET_{nb}=EVTR_{nb}\qquad h_n>SURF_{nb}$$

When the depth of the water table below the $SURF_{nb}$ elevation exceeds a specified interval, termed the “extinction depth” ($EXDP_{nb}$), ET from the water table ceases:

$$RET_{nb} = 0 \qquad h_n < (SURF_{nb} - EXDP_{nb})$$

Between these limits, ET from the water table varies in a piecewise-linear fashion:

$$RET_{nb} = EVTR_{nb} \frac{h_n - (SURF_{nb} - EXDP_{nb})}{EXDP_{nb}} \qquad (SURF_{nb} - EXDP_{nb}) \leq h_n \leq SURF_{nb}$$

The volumetric rate of ET (QET_{nb}) is computed as a product of RET_{nb}, the horizontal surface area of the cell from which the loss occurs, A_n, and a dimensionless multiplier (M_{nb}).

Unsaturated Zone Flow (UZF) Package

Evaporation and uptake by roots are grouped together and occur as an instantaneous loss of water over a depth interval equal to the depth of the root uptake. While evaporation can cause water to move upward in the unsaturated zone by drying out the soil at land surface or by upward flow from the water table into the capillary zone, this process is not simulated in the UZF package.

ET in the unsaturated zone is calculated as:

$$q_{UZET_p} = K(\theta_p)[\varphi(\theta_p) - h_{root_{nb}}]$$

Where q_{UZET_p} is the unsaturated zone ET for UZF boundary at point *p*, $\varphi(\theta_p)$ is sediment capillary pressure in UZF boundary *nb* at point *p*, and $h_{root_{nb}}$ is the user-specified negative root pressure for UZF boundary *nb*.

Groundwater ET is simulated in the UZF Package when the extinction depth (Dext) value exceeds the depth to water in a cell. Water is only taken from the saturated zone if PET exists beyond water available in the unsaturated zone. The UZF package uses either a linear decrease in groundwater ET (equivalent to the ET package) or represents a square ET function and assumes a constant ET rate over the Dext and a cubic smoothing curve over a small interval:

$$QUGET_{nb} = S_{UGET,n} A_n RPET_{nb}$$

Where QUGET is the volumetric rate of ET removed from cell n connected to UZF boundary nb, S is a smoothing function that scales the remaining PET

$$S_{UGET,n} = \begin{cases} -2\beta^3 + 3\beta^2 & for\ 0 < \beta < 1 \\ 1 & for\ 1 \leq \beta \\ 0 & for\ \beta \leq 0 \end{cases}$$

Where is a relative height of the water above Dextnb for UZF boundary nb and is calculated as:

$$\beta = \frac{h_n - z_{nb}}{c}$$

Where znb is the depth below which smoothing occurs:

$$z_{nb} = D_{ext_{nb}} - c$$

Where c is a smoothing interval above D. The specified infiltration rate is converted to water content in the UZF Package:

$$\begin{aligned} \theta_{q_a} &= \left(\frac{q_a}{K_{sat}}\right)^{1/\varepsilon} (\theta_{sat} - \theta_{resid}) + \theta_{resid} \quad && 0 \leq q_a \leq K_{sat} \\ \theta_{q_a} &= \theta_{sat} && K_{sat} < q_a \end{aligned}$$

Where θ_{q_a} is the water content from infiltration and q_a is the volumetric infiltration rate per unit area.

Percolation
Water that exits the aquifer through the deepest layer should be governed by the boundary conditions set by the user on these cells.

Lateral subsurface flow
NA

Channel Routing
The Streamflow Routing (SFR) Package computes streamflow such that during all times, volumetric inflow and outflow rates are equal and no water is added to or removed from storage in the surface channels to route streamflow through a network of rectangular channels.

Inflow to a stream reach:

$$QIN_{nb} = QSRI_{nb} + QTRB_{nb} + QRO_{nb} + QMVR_{nb} + QPPT_{nb} - QSFRI_{nb}$$

- $QSRI_{nb}$ is a user specified inflow
- $QTRB_{nb}$ is a user specified sum of tributary flow from upstream reaches
- QRO_{nb} is direct overland runoff to a reach
- $QMVR_{nb}$ is inflow from the Mover Package
- $QPPT_{nb}$ is precipitation that falls directly on a reach
- $QSFRI_{nb}$ is groundwater leakage to a reach calculated by the model

Losses from a stream reach:

$$QOUT_{nb} = QSRO_{nb} + QDIV_{nb} + QET_{nb} + QSFRO_{nb}$$

- $QSRO_{nb}$ is user specified streamflow out of a reach
- $QDIV_{nb}$ is specified diversions from another reach
- QET_{nb} is evaporation from a reach
- $QSFRO_{nb}$ is leakage to the underlying aquifer

Thus:

$$Q_{nb} = QSRI_{nb} + QTRB_{nb} + QMVR_{nb} + 0.5(QRO_{nb} + QPPT_{nb} - QET_{nb} - QSFR_{nb})$$

For active reaches the SFR Package uses Manning's equation to determine stream depth as a function of streamflow, then the stream depth is used for the next stream reach downstream:

$$Q_{nb} = \frac{C_u}{n_{nb}} W_{nb} D_{nb}^{5/3} So_{nb}^{1/2}$$

- Q_{nb} is the stream discharge at the midpoint of reach nb
- C_u is a units constant (cms vs cfs)
- n_{nb} is Manning's roughness coefficient
- D_{nb} is the stream depth at the midpoint of reach nb
- So_{nb} is slope of the stream channel

Ground Water Routing

Represented by the Groundwater Flow (GWF) model of MODFLOW6. This process is a grid of cells, where flow travels from cell to cell. The GWF is divided into packages which simulate a single aspect of the model which seem to be optional:

- Discretization
- Initial Conditions
- Node Property Flow
- Horizontal Flow Barrier
- Ghost Node Correction
- Storage
- Specified Head
- Well
- Recharge
- River
- General-Head Boundary
- Drain
- Evapotranspiration
- Stream-Flow Routing
- Lake
- Multi-Aquifer Well
- Unsaturated Zone Flow
- Water Mover
- Model Observations
- Output Control

Three-dimensional movement of groundwater of constant density through porous earth material is described by Darcy's Law:

$$q = -K\nabla h = -\begin{pmatrix} K_{xx} & 0 & 0 \\ 0 & K_{yy} & 0 \\ 0 & 0 & K_{zz} \end{pmatrix}\nabla h$$

where:

- q is a vector of specific discharge
- K is hydraulic conductivity
- h is potentiometric head
- ∇h is the head-gradient vector

when combined with a water balance on a small control volume, Darcy's Law leads to a partial-differential equation that describes the distribution of hydraulic head:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) + Q_s' = SS\frac{\partial h}{\partial t}$$

- Q_s' is a volumetric flux per unit volume representing sources and sinks of water
- SS is the specific storage of the porous material
- t is time

The GWF Process uses the Control-Volume Finite-Difference Method (CVFD) to numerically approximate the solution to the continuous equation above. In the CVFD, the continuous equation is replaced by a finite set of discrete points in space and time, and the partial derivatives are replaced by terms calculated from the differences in head values at these points.

Flow between cells of the grid

$$Q_{n,m} = \overline{K}_{n,m}\Delta w_{n,m}\Delta v_{n,m}\frac{h_m - h_n}{L_{n,m} + L_{m,n}}$$

- $Q_{n,m}$ is the flow rate into cell *n* from cell *m*
- $K_{n,m}$ is the effective hydraulic conductivity between the cells
- $\Delta w_{n,m}$ is the width of the face through which flow occurs
- $\Delta v_{n,m}$ is the height of the face through which flow occurs
- h_n is the head in cell *n*
- h_m is the head in cell *m*
- $L_{n,m}$ is the distance from the center of cell *n* to its shared face with cell *m*
- $L_{m,n}$ is the distance from the center of cell *m* to its shared face with cell *n*

The hydraulic conductivity is combined with grid dimensions to form the "conductance"

$$C_{n,m} = \frac{\overline{K}_{n,m}\Delta w_{n,m}\Delta v_{n,m}}{L_{n,m} + L_{m,n}}$$

- $C_{n,m}$ is the conductance between cells *n* and *m*

So:

$$Q_{n,m} = C_{n,m}(h_m - h_n)$$

External sources and sinks (external flow)
To account for flows into the cell from features or processes external to the aquifer (i.e., rivers, drains, areal recharge, evapotranspiration) additional terms are required. External flows may either be dependent on the head in the receiving cell or independent of the head in the receiving cell:

$$Q_{n,s} = \sum_{isrc=1}^{nsrc} a_{n,isrc} = \sum_{isrc=1}^{nsrc} p_{n,isrc}\, h_n + \sum_{isrc=1}^{nsrc} q_{n,isrc}$$

- $Q_{n,s}$ external flow term for cell *n*
- $a_{n,isrc}$ is flow from external source *isrc* to cell *n*
- $p_{n,isrc}$ is the head coefficient used in the flow calculation
- $q_{n,isrc}$ is the head independent term used in the flow calculation

Water Balance on a Cell

$$\sum_{m\in\sigma_n} Q_{n,m} + Q_{n,s} - Q_{STO} = 0$$

- σ_n is a list of the cells connected to cell n
- $Q_{n,m}$ is the flow rate into cell n from cell m
- $Q_{n,s}$ is the flow rate of sources and sinks into cell n
- Q_{STO} is defined as:

$$Q_{STO} = SS_n \frac{\Delta h_n}{\Delta t} V_n$$

- SS_n is the volume of water that can be added or removed per unit volume of aquifer material per unit change in head in cell *n*
- V_n is the volume of cell *n*
- Δh_n is the change in head in cell *n* over a timer interval of length Δt

Additional Information
Includes a Well (WEL) Package to simulate features that withdraw water from or add water to the aquifer at a specified rate during a time period.
Includes a River (RIV) Package to simulate the effects of flow between surface-water features (rivers and streams) and groundwater systems.
Includes a Drain (DRN) Package to simulate the effects of agricultural drains, springs, and features that remove water from the aquifer at a rate proportional to the difference between the head in the aquifer and some fixed head or elevation.
Includes an advanced Lake (LAK) Package to simulate the relationship between a lake and an adjacent aquifer.
Included in the UZF package is an option to simulate groundwater seepage to the land surface (spring discharge).

APPENDIX F: Hydrologic comparison template for the WPD Parsimonious model.

Parsimonious Model

General Information

Model History

The original purpose of this model was to quantify the impacts of a riparian zone on the water quality of a receiving stream in a parsimonious manner. The model is based on the collation of three sources hybridized with equations from soil physics and groundwater mechanics. The three sources are from a paper describing a parsimonious model for surface runoff, another publication modeling upland subsurface flow in parallel with riparian subsurface flow, and a final paper on areal aggregation of soil properties throughout a watershed (Craig et al. 2010; Bear 2013; Fovet et al. 2015).

Abel Porras created the model in 2017 after discussion within ERM on the lack of such a model. There have been no changes, but there is an effort to incorporate a GUI into the model.

Source (Open/Proprietary)

Open source

Maintenance

Abel Porras maintains this model in-house.

Model Uses

16. Hydrology, nutrient transport are the primary mechanisms being studied.
17. How are SCMs incorporated?
    a. SCMs can be routed through the either the upland subsurface flow module or the riparian subsurface flow module.
18. Duration of Model Run
    a. Minimum/Maximum Time Step
       There is no minimum or maximum time step. The only restrictions are on the number of rows in Excel or the patience of the user to go through the rows in Excel.

Calibration Method

There are no calibration routines in the model.

Suggested Tools for Data Entry

Data entry can be done by copy-paste controls and/or importing a time series of rainfall values.

Watershed Configuration

Configured in an Excel Workbook

Land Surface

Area to be simulated: Basin

Land unit distribution: Lumped

Hydrologic unit(s) of land whose topography and drainage system elements direct surface runoff to a single discharge point: Subcatchment

- Minimum/Maximum Unit Size: The minimum unit size is about 1 ac. The maximum unit size is the size limits governed by the SCS Curve Number method.

Distribution of Impervious/Pervious Land:

- Subcatchments of different pervious and impervious subareas can either remain segregated or can be averaged using a weighting approach.

Flow Pathway

Inflow or Discharge Points: Nodes

- Points of conveyance, and if using Excel, are represented in a worksheet.
- Each worksheet will have time in rows, and thus will produce a hydrograph at each node.
- Different worksheets will contain calculations for different nodes. Junction of the nodes can be summed in a separate worksheet.
- Each worksheet provides flow rates and hydrographs at each node

Primary flow pathway (channel, pipes, etc.): NA.

Additional Information

Weather (include time step for applicable fields)
Rain: Closest rain gage to subcatchment (if gages provide 15 min increments rainfall totals, then this equals 4 increments/hr x 24 hr/day x 365 day/yr = 35,000 rows in an Excel sheet) or any COA design storm hyetograph can be input into model, which will require a smaller number of Excel rows.

Temperature:

Wind Speed:

Relative Humidity:

Solar Radiation:

Forecast data:

Snow:

Climate Change:

Surface Runoff and Soil Routing

Inputs/Outputs

Subcatchment inputs = precipitation
Subcatchment outputs = surface runoff

Precipitation

Rain (defined in the weather section above)

Surface Runoff

SCS Curve Number method. Runoff occurs when the initial abstraction in soil is met. After that point, the abstraction in the soil is a function that decays with time. That is, the soil still needs some precipitation input to maintain saturation, but the quantity required by soil decreases and can be used as one of two calibration factors. The remaining precipitation is surface runoff. Multiply by the watershed area to get cfs.

- Runoff from one subarea (impervious/pervious) in a subcatchment can be routed to the other subarea or both can drain to the subcatchment node, but must be specified by user.

Infiltration

Infiltration into the unsaturated upper soil zone is described by SCS Curve Number.

Evapotranspiration

NA

Percolation

No water moving into a deep aquifer in the model

Lateral subsurface flow

See Ground Water Routing

Channel Routing

NA

Ground Water Routing

Represented by an unsaturated zone and a saturated zone. Parameters of an aquifer can be shared by several subcatchments. We can exchange groundwater flow between subcatchments (see routing graphic above).

- Flow through the unsaturated zone is represented by a linearized version of Richards' Equation and provides the level of saturation at each depth for each increment of time. That equation is:

  $$\theta(z,t) = \theta_D + \frac{\theta_W - \theta_D}{2}\left\{erfc(\Gamma - \omega) + \exp\left(\frac{kz}{D}\right) erfc(\Gamma + \omega)\right\}$$

  Where

  $$\Gamma = \frac{z}{2\sqrt{(Dt)}} \text{ and } \omega = \frac{k}{2}\sqrt{\frac{t}{D}}$$

- As the saturated front moves through the vadose (i.e. unsaturated) zone, it will form a temporary "mound" above the water table. That "mound" will provide hydraulic head, H_0, to the aquifer, which will result in additional lateral flow in the aquifer to the stream. This lateral flow in an unconfined aquifer is difficult to model, but can be simplified by using the Dupuit-Forchheimer assumptions.
- Flow through the saturated zone is represented by a linearized version of the Boussinesq Equation, which simplifies the assumptions of Dupuit- Forchheimer assumptions.

- The outflow rate from the saturated zone to the stream is characterized by the following equation (Bear 2013):

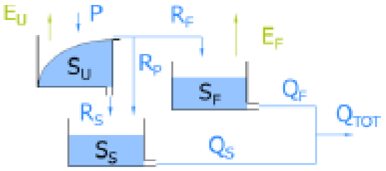
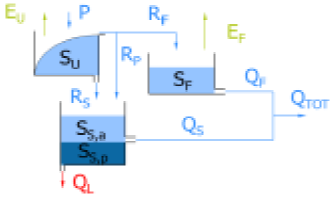
$$Q = 2(H_0 - T)K_S H_0 / \sqrt{4\pi K_S H_0 t / \eta_E}$$

- Saturated Zone and Unsaturated Zone Parameters are:
    - η_E = Porosity (volumetric fraction)
    - K_S = Conductivity or the soils saturated hydraulic conductivity
    - T = Thickness of unconfined aquifer or Water Table Elevation - Bottom Elevation
    - H_0 = Height of saturation from mounding due to precipitation.
    - θ_W = Wilting Point (volumetric fraction)
    - θ_D =Field Capacity (volumetric fraction) soil moisture content after all free water has drained
    - k = Slope of Conductivity vs. Soil Moisture Content
    - D = soil water diffusivity

Additional Information

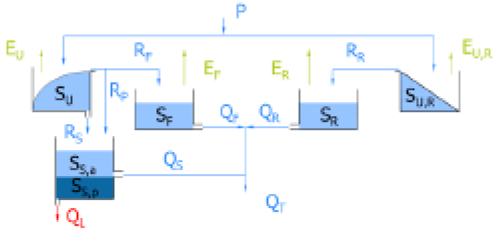
For the segregation case, volumes of surface water and subsurface water can be manually routed either in series or in parallel (see graphic below). Formulae also exist for the averaged case (Craig et al. 2010).

Table 2. Model structures and parameters.

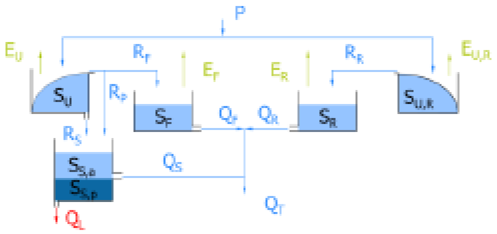
Model structure	Name
	M1
	M2

For these two models (M1 and M2), precipitation is directly routed through some averaged subcatchment to the stream. For the two models below (M3 and M4), precipitation is routed to two subcatchments within a watershed basin (say a riparian subcatchment and a developed subcatchment) in parallel to the stream. This allows distinct subcatchments to influence stream flow in different ways but calls for more parameters to input (Fovet et al. 2015).

M3



M4



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APPENDIX G: Hydrologic comparison template for SWAT.

Soil and Water Assessment Tool (SWAT)

General Information

Model History

SWAT was created in the early 1990s through the merging of the Routing Outputs to Outlet (ROTO) model and the Simulator for Water Resources in Rural Basins (SWRRB). The SWRRB model was developed in the late 1980s and based on the Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model with a focus on water quality assessment and watershed management. Modifications from the CREAMS model included simultaneous computations on serval subbasins, a return flow component, reservoir storage, a weather simulator, peak runoff prediction was altered, the EPIC crop growth model was added, flood routing, and sediment transport.

In the late 1980s, the Bureau of Indian Affairs needed a model to estimate the downstream impact of water management within Indian reservation lands in Arizona and New Mexico. While SWRRB was easily utilized for watersheds up to a few hundred square kilometers in size, the Bureau also wanted to simulate stream flow for basins extending over several thousand square kilometers. For an area this extensive, the watershed under study needed to be divided into several hundred subbasins. Watershed division in SWRRB was limited to ten subbasins and the model routed water and sediment transported out of the subbasins directly to the watershed outlet. These limitations led to the development of a model called ROTO (Routing Outputs to Outlet), which took output from multiple SWRRB runs and routed the flows through channels and reservoirs. ROTO provided a reach routing approach and overcame the SWRRB subbasin limitation by "linking" multiple SWRRB runs together. To overcome the burden of linking these two models together they were merged into SWAT.

Source (Open/Proprietary)

Open Source

Maintenance

Texas A&M AgriLife Research

Model Uses

19. Hydrology, nutrient transport, sediment transport, other pollutants?
    Rainfall runoff and return flow, channel flow, nutrient transport, sediment transport, simulation of irrigation practices, simulation for different crop types, simulation of structural controls
20. How are SCMs incorporated?
    Controls throughout a land segment are aggregated at most portion of the land segment. Stormwater passes through the control and then is sent to the creek or is infiltrated within the control. The hydraulic conductivity and storage volume of a control is set within BMP files.
21. Duration of Model Run
    a. Minimum/Maximum Time Step
       Built for long-term simulations, minimum/maximum time step undocumented

Calibration Method

Autocalibration via a program called SWAT-CUP

Suggested Tools for Data Entry

ArcSWAT, an ArcGIS interface to SWAT

Watershed Configuration

Land Surface

Area to be simulated: Basin

Land unit distribution: Lumped

Hydrologic unit(s) of land whose topography and drainage system elements direct surface runoff to a single discharge point: Subbasin

- Subbasins are broken up into HRU.
- HRUs are homogeneous area within a subbasin with a unique combination of land use, soils, and slope. Not spatially located, but water balance info can be found at HRU level.
- Minimum/Maximum Unit Size: Undocumented

Distribution of Impervious/Pervious Land: HRUs have an impervious cover associated with them

Flow Pathway

Inflow or Discharge Points: Outlet.

- Outlets exist at bottom of a subbasin. There is an outlet at the upstream and downstream end of each reach. No physical characteristics of an outlet, just a location to output flow and concentrations. Outlets must also be added (which will form more subbasins) for any desired inputs (e.g. point sources), or online ponds need to be located.

Primary flow pathway (channel, pipes, etc.): Reaches.

- Trapezoidal flow channels connecting two outlets.
- Tributary subbasin channels are minor channels branching off the main channel; can be present or not in headwater subbasin. The tributary channels represent concentrated upland flow, only route a portion of the subbasin (so a portion has a longer time of concentration). Do not receive groundwater return flow.

Additional Information

Other flows (point sources, upstream model inflow, removal of water pumping, irrigation, lateral flow to creek, etc.) are simply added to the water balance in the appropriate place. Point sources added to the channel, water pumping from subtracted from appropriate aquifer level, irrigation added to rainfall (for HRUs where applied), lateral flow added (or subtracted) to/from creek, etc. A route or pathway does not need to be specified for these pathways except for specifying source of irrigation water (may also be "outside of watershed".

Weather (include time step for applicable fields)
Specified in file.cio
If data is not available it is simulated from statistical data at various US gages provided

Rain: Closest rain gage to subbasin.

Temperature: Supplied to SWAT as a user-defined time series of point values containing daily min/max.

Wind Speed: Supplied by user.

Relative Humidity: Supplied by user.

Solar Radiation: Supplied by user.

Forecast data: Will generate forecast period using US National Weather Service data for their regions. Multiple simulations to obtain a distribution of possible weather scenarios with a minimum of 20 cycles recommended.

Snow: Parameters supplied by the user in the .bsn file.

- Snow melt
- Cover
- Can specify elevation bands

Climate Change: Simulate climate change by adjusting input data or set adjustment factors.

- % change in rainfall for month
- Increase or decrease in temp for month
- Increase or decrease in solar radiation
- Increase or decrease in relative humidity
- CO2 level in subbasin

Surface Runoff and Soil Routing

Specified in .bsn file

Inputs/Outputs

Subbasin inputs = precipitation + overland flow from upstream subbasin

Subbasin outputs = infiltration + evapotranspiration + surface runoff + percolation + return flow to creek

Precipitation

Rain & Snowmelt (defined in the weather section above)

- Canopy storage can intercept and store precipitation
- If using daily rainfall then this value is implicit in the curve number method
- If using sub-daily rainfall then uses f(leaf area index, time in growth cycle)

Surface Runoff

- Daily: Modification of SCS Curve Number method, where the retention parameter varies with soil moisture content
- Subdaily: Use the Green&Ampt Mein-Larson to calculate infiltration. For each time step, SWAT calculates the amount of water entering the soil. The water that does not infiltrate into the soil becomes surface runoff.
- Time of Concentration is the amount of time from the beginning of a rainfall event until the entire subbasin area is contributing to flow at the outlet. Subbasin time of concentration is estimated using manning's and longest flow path.
- For subbasins with long Time of Concentration, it may take longer than a day for runoff to reach the main channel. Thus water can be lagged for future use. Runoff reaching the main channel is lagged using the SURLAG coefficient and the time of concentration (based on flow-length and avg. velocity)

Infiltration

- Daily model: infiltration is just the Rain minus the Runoff, where runoff is calculated using the modified SCS Curve Number method.
- Sub-daily: Green&Ampt Mein-Larson calculates infiltration as f(wetting front matric potential, change in volumetric moisture content across the wetting front, cumulative infiltrations, and effective hydraulic conductivity)

Evapotranspiration

Evaporation is first taken from the Canopy Storage. Potential ET methods include Hargreaves, Priestly-Taylor, or Penman-Monteith.

- ETplants = f(PET, leaf area index) or measured ET
- ETsoilwater = f(soil depth, water content)
- Soil water, where the content is between the field capacity and the permanent wilting point is available for plant extraction.

Percolation

Calculated for each of the 10 soil layers. When the water content exceeds the field capacity water content for that layer and the layer below is not saturated then water travels down to the layer below. Water that percolates out of the lowest soil layer enters the vadose zone. Allows for bypass of soil layers due to soil cracks.

Lateral subsurface flow

Lateral subsurface flow occurs when water content of a soil layer exceeds the field capacity water content for that layer but the layer below is saturated. Kinematic storage model used to predict lateral flow in each soil layer as f(conductivity, slope, soil-water content).

Channel Routing

Flow routing occurs within reaches which always lie between a pair of outlets. The flow calculation methods are:

- Variable storage routing

$$q_{out,2} = SC\left(q_{in,ave} + \frac{V_{stored,1}}{\Delta t}\right)$$

$$SC = \frac{2 * \Delta t}{2 * TT + \Delta t}$$

Then both sides are multiplied by the time step to express in units of volume:

$$V_{out,2} = SC\left(V_{in} + V_{stored,1}\right)$$

  - $q_{out,2}$ is the outflow rate at the end of the time step
  - $q_{in,ave}$ is the average inflow rate during the time step
  - $V_{stored,1}$ is the storage volume at the beginning of the time step
  - Δt is the length of the time step
  - TT is the volume of water in the channel divided by the flow rate

- Muskingham river routing which models the storage volume in a channel length as a combination of wedge and prism storages. The wedge is used for flood waves (variation of the kinematic wave model)

$$q_{out,2} = C_1 q_{in,2} + C_2 q_{in,1} + C_3 q_{out,1}$$

$$C_1 = \frac{\Delta t - 2KX}{2K(1-X) + \Delta t}$$

$$C_2 = \frac{\Delta t + 2KX}{2K(1-X) + \Delta t}$$

$$C_3 = \frac{2K(1-X) - \Delta t}{2K(1-X) + \Delta t}$$

Then both sides are multiplied by the time step to express in units of volume:

$$V_{out,2} = C_1 V_{in,2} + C_2 V_{in,1} + C_3 V_{out,1}$$

  - $q_{in,2}$ is the inflow rate at the end of the time step
  - $q_{in,1}$ is the inflow rate at the beginning of the time step
  - $q_{out,1}$ is the outflow rate at the beginning of the time step
  - K is the storage time constant for the reach
  - X is a weighting factor which is a function of the wedge storage ($0.0 < X < 0.5$)

There is evaporation from creeks and transmission, losses through the bed of the channel. within tributary and main channels. Transmission losses are based on flow duration, depth and width of flow and effective hydraulic conductivity of the channel alluvium. Losses are assumed to percolate to the shallow aquifer.

Ground Water Routing

Two aquifers in each subbasin. Shallow aquifer is unconfined and contributes to flow in the main channel. Deep aquifer is confined and water that enters is assumed to contribute to streamflow outside of the watershed.

Water Balance Equations

$$aq_{sh,i} = aq_{sh,i-1} + w_{rchrg,sh} - Q_{GW} - w_{revap} - w_{pump,sh}$$

$$aq_{dp,i} = aq_{dp,i-1} + w_{deep} - w_{pump,dp})$$

- $aq_{sh,i}$ is the volume of the shallow aquifer on day i
- $aq_{sh,i-1}$ is the volume of the shallow aquifer on day i-1
- $w_{rchrg,sh}$ is the amount of recharge entereing the shallow aquifer
- Q_{GW} is the groundwater flow, or base flow, into the main channel
- w_{revap} is the amount of water moving into the soil zone in response to water deficiencies
- $w_{pump,sh}$ is the amount of water removed from the shallow aquifer by pumping
- $aq_{dp,i}$ is the amount of water stored in the deep aquifer on day i
- $aq_{dp,i-1}$ is the amount of water stored in the deep aquifer on day i-1
- w_{deep} is the amount of water percolating from the shallow aquifer to the deep
- $w_{pump,dp}$ is the amount of water removed from the deep aquifer by pumping

Recharge

Water that percolates out of the bottom of the soil profile or bypass flow from cracks enters the vadose zone before becoming shallow and/or deep aquifer recharge. A time lag is calculated using an exponential decay function. The amount of recharge to both aquifers is given by:

$$w_{rchrg,i} = \left(1 - exp\left(\frac{-1}{DT}\right)\right) * w_{seep} + exp\left(\frac{-1}{DT}\right) * w_{rchrg,i-1}$$

where DT = user defined delay time, and w_{seep} the amount exiting the bottom of the soil profile. Recharge going to the deep aquifer is equal to the aquifer percolation coefficient (β_{deep}) multiplied by the w_{rchrg}. The amount going to the shallow aquifer is just the total recharge minus the amount going to the deep aquifer.

Baseflow/Return Shallow Groundwater

Return flow to the main channel occurs if the shallow aquifer storage exceeds a user-specified threshold $aq_{shthr,\ q}$.

$$Q = Q_{gw,i-1} * \exp(-\alpha_{bf} * dt) + w_{rchrg,sh}\left(1 - exp(-\alpha_{bf} * dt)\right)$$

α_{bf} is a user defined baseflow recession constant of GW flow response. Baseflow days (BFD) is the #days for recession curve to decline through one log cycle. When in days, α_{bf} = 2.3/BFD

Revap

Movement of water from shallow aquifer into overlying unsaturated layers as a function of water demand from ET.

Additional Information

Tributary channels are branches from the main channel and channelized flow in the headwater subbasins. Tributary channels are used to determine time of concentration for surface runoff and allow percolation in the concentrated flow areas.

APPENDIX H: Hydrologic comparison template for SWMM.

StormWater Management Model (SWMM)

General Information

Model History

Original purpose of the model was for evaluation of combined sewer overflows (CSOs) and sanitary sewer overflows (SSOs) especially for complex hydraulics. Original development was in 1969-71 by Metcalf and Eddy, Water Resource Engineers, Inc. (WRE, now CDM), and Univ. of Florida. Written originally in open Fortran source code, it's been developed continuously since. Contributors include EPA-CEAM, CDM, Universities of Guelph, Florida and Oregon. Major leaps were EXTRAN dynamic flow routing, solution of saint venant equations (based on SWMM Receiv and SF Bay Estuary model) and continuous simulation (based on Stanford WM). Released in 1977. EPA-CEAM released first PC version in 1983 v3.3. GIS version released in 1989. Multiple GUIs versions released in 1990's including XP-SWMM, PCSWMM, Visual SWMM, MIKE-SWMM, using SWMM v4.x still in Fortran. Current on release v5.1.013 (8/09/2018) at https://www.epa.gov/water-research/storm-water-management-model-swmm

Source (Open/Proprietary)

SWMM 5 was re-written in ANSI standard C by EPA (Lew Rossman) in 2011 with a public domain GUI although there are still lots of proprietary GUIs operating with it. They pumped up the open source aspect with an https://www.openswmm.org/ site with code viewer and collaboration/knowledge base pages, and http://www.ncimm.org/ center for supporting SWMM and corresponding EPANET for water distribution network model, and link to information about changes in federal open source code policy https://sourcecode.cio.gov/

Maintenance

USEPA Office of Research and Development National Risk and Management Research Laboratory https://www.epa.gov/water-research/storm-water-management-model-swmm

Contact: Michelle Simon, 513-569-7469
Email: simon.michelle@epa.gov

A SWMM users' listserv was established by the University of Guelph. This listserv allows subscribers to ask questions and exchange information. To subscribe, send an email message to listserv@listserv.uoguelph.ca with the words subscribe swmm-users in the subject line and your name in the body of the email.

Model Uses

22. Hydrology, nutrient transport, sediment transport, other pollutants?
    Hydraulic modeling to route runoff and external flow through the drainage system network of pipes, channels, storage/treatment units, and diversion structures. Hydrologic processes include runoff via green infrastructure, time-varying rainfall and evaporation, interception, infiltration into unsaturated soil layers, percolation into groundwater layers, and reservoir routing. Estimates the pollutant loads associated with stormwater runoff. Also include a software utility that allows future climate change projections to be incorporated into modeling via the SWMM Climate Adjustment Tool (SWMM-CAT).
23. How are SCMs incorporated?
    Reduction in constituent concentration through percent removal treatment specified by user in storage units, pipes, and channels. Reduction in wash-off loads by percent removal from specific land-use

types. Reduction in dry-weather buildup due to street cleaning applied to land-use type. Explicitly model generic green infrastructure practices via the BMP tool kit.

24. Duration of Model Run
    a. Minimum/Maximum Time Step
       SWMM allows the user to specify two different time steps that will be used when evaluating surface runoff during a simulation: a "wet" step and a "dry" step. The wet time step is used when there is precipitation or overland flow on any sub-catchment within the study area. The longer dry time step applies when there is both no precipitation input and all depression storage remains unfilled. In addition, a smaller time step is used for hydraulic flow routing. Wet time step default is 5min and dry time step default is 1 hour. When variable time steps are used for dynamic wave flow routing, the minimum time step allowed default is 0.5 seconds.

Calibration Method

Several calibration methods have been developed including manual methods, genetic algorithms, Powell method, Rosenbrock's method, Box Complex method, Excel solver, Neural network, GLUE algorithm, PCSWMM 2000 autocalibration, InfoWorksCS autocalibration, NSGAII algorithm, Shuffled complex evolution, and a few expert systems.

Suggested Tools for Data Entry

New GUI for SWMM v5. The new public domain GUI for SWMM built in v5 adds to the many proprietary versions available prior to that including PCSWMM and XP-SWMM, MIKE-SWMM, and Visual SWMM. The public domain version seemed to be just bringing in a drawing of the watershed and drainage infrastructure, drawing the sub-catchments and watersheds over it, then assigning the parameters to the nodes and catchments with various menus. The GIS processing must be done to the side to get catchment parameters in more of a batch manner when there are too many catchments enter in pull down menus.

Watershed Configuration

Land Surface

Area to be simulated: Study area. This would be the watershed in a larger model but could be a site in a higher resolution model.

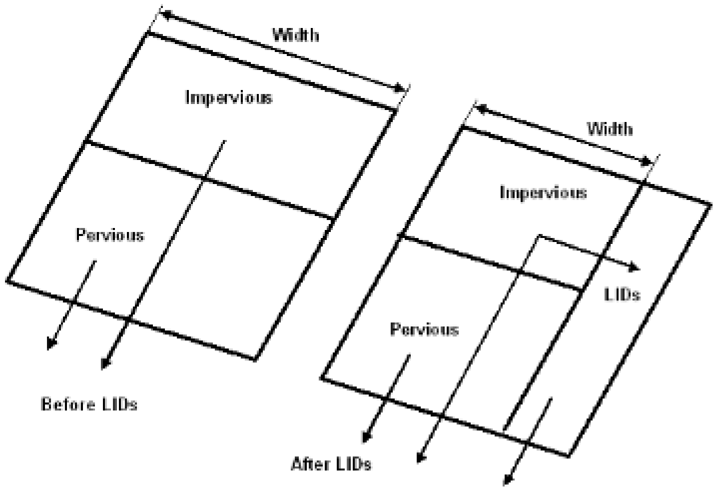
Land unit distribution: Lumped

Hydrologic unit(s) of land whose topography and drainage system elements direct surface runoff to a single discharge point: Subcatchments

- Minimum/Maximum Unit Size: Undocumented

Distribution of Impervious/Pervious Land:

There are a few different ways to route overland flow within the area. the impervious can flow over pervious and take advantage of infiltration and different soil properties, or it can split and part of the overland flow can go over a third are representing LIDs before leaving the area. The overland flow can also be collected in a single drain or the LID outflow can be collected in a separate drain.



Flow Pathway

Inflow or Discharge Points: Nodes.

- Nodes can be points where external inflows can be added to a drainage system, removal of pollutants through treatment occur, and are one of two possible discharge outlet points for subcatchments.
- Categorized as junctions, outfalls, flow dividers, storage units.
    - Junctions are drainage system nodes where links join together. Physically they can represent the confluence of natural surface channels, manholes in a sewer system, or pipe connection fittings. External inflows can enter the system at junctions.
    - Outfalls are terminal nodes of the drainage system used to define final downstream boundaries under Dynamic Wave flow routing. For other types of flow routing they behave as a junction. Only a single link can be connected to an outfall node, and the option exists to have the outfall discharge onto a subcatchment's surface.
    - Flow Dividers are drainage system nodes that divert inflows to a specific conduit in a prescribed manner. A flow divider can have no more than two conduit links on its

    discharge side. Flow dividers are only active under Steady Flow and Kinematic Wave routing and are treated as simple junctions under Dynamic Wave routing.
    - Storage Units are drainage system nodes that provide storage volume. Physically they could represent storage facilities as small as a catchbasin or as large as a lake. The volumetric properties of a storage unit are described by a function or table of surface area versus height. In addition to receiving inflows and discharging outflows to other nodes in the drainage network, storage nodes can also lose water from surface evaporation and from seepage into native soil.

Primary flow pathway (channel, pipes, etc.): Links.

- Always lie between two nodes.
- Categorized as conduits, pumps, or regulators
    - Conduits pipes or channels that move water from one node to another in the conveyance system. Their cross-sectional shapes can be selected from a variety of standard open and closed geometries. Irregular natural cross-section shapes are also supported, as are user-defined closed shapes.
    - Pumps are links used to lift water to higher elevations.
    - Regulators are structures used to control and divert flows within the conveyance system. Typically used to control releases from storage facilities or divert flow to treatment facilities and interceptors. Categorized as orifices, weirs, or outlets.
        - Orifices are used to model openings in the wall of a manhole, storage facility, or control gate.
        - Weirs are typically located in a manhole, along a channel, or within a storage unit. The weir is placed at the upstream node of the link.
        - Outlets typically used to control outflows from storage units.

Weather (include time step for applicable fields)

Rain: Rain gages supply precipitation data to one or more subcatchment areas in a study region. Data can either be a user-defined time series or imported from an external file. External files currently recognized are hourly and fifteen-minute precipitation data retrieved from NOAA’s National Climatic Data Center (NCDC) Climate Data Online service (www.ncdc.noaa.gov/cdo-web).

Temperature: Supplied to SWMM either as a user-defined time series of point values (values at intermediate times are interpolated) or an external file containing daily minimum and maximum values (SWMM fits a sinusoidal curve through these values depending on the day of the year).

- Used when simulating snowfall and snowmelt processes during runoff calculations and are not required if these processes are not being simulated.

Evaporation: Supplied as a single constant value, set of monthly average values, user-defined time series, values computed from the daily temperatures contained in an external climate file, or daily values read from an external climate file. Evaporation rates supplied to SWMM are potential rates.

Wind Speed: Supplied as a set of monthly average speeds or supplied in the same climate file used for the daily minimum/maximum temperatures.

- Only used for snowmelt calculations.

Snowmelt: Parameters supplied by the user that apply across the entire study area.

- Air temperature at which precipitation falls as snow
- Heat exchange properties of the snow surface
- Study area elevation, latitude, and longitude correction
- Areal depletion curves can be supplied by the user, one for impervious area and one for pervious area, which plots the fraction of total area that remains snow covered against the ratio of the actual snow depth to the depth at which there is 100% snow cover.

Climate Change: Climate Adjustments. SWMM offers optional modifications applied to the temperature, evaporation rate, and rainfall intensity. Provide a simple way to examine the effects of future climate change without having to modify original climatic time series.

Surface Runoff and Soil Routing

Inputs/Outputs
Subcatchment inputs = precipitation + runoff from upstream subcatchment
Subcatchment outputs = infiltration + evaporation + surface runoff

Precipitation
Rain & Snowmelt (defined in the weather section above)

Surface Runoff
SWMM calculates the amount of water entering the soil and then allows water to pond at the surface. Subcatchment surface runoff occurs only when depth of water in the subcatchment (d) exceeds the maximum depression storage (ds) for that subcatchment.

$$Runoff = \left(\frac{1.49}{n}\right) * Area * Slope^{1/2} * (d - d_s)^{5/3}$$

The depth of water (d) over the subcatchment is updated at the end of every time step.

Infiltration
Described by Classical Horton, Modified Horton, Green-Ampt, Modified Green-Ampt, or Curve Number Methods. Infiltrated water will go into the unsaturated upper soil zone. Unless the groundwater aquifer is turned on for the subcatchment, any volume of water that is infiltrated will be lost.

Evapotranspiration
Evaporation can either be input as described in the weather section above or if the “Computed from Temperatures” option is chosen, the Hargreaves method will be used to compute daily evaporation rates from the daily air temperature record contained in the external climate file.

Percolation
Water that percolates from the upper zone to the lower zone and from the lower zone out of simulation is described in the Ground Water Routing section below.

Lateral subsurface flow
Water that moves in the subsurface is discussed in the Ground Water Routing section below.

Channel Routing

Flow routing occurs within a conduit link and is governed by the conservation of mass and momentum equations for gradually varied, unsteady flow (i.e., the Saint Venant flow equations). Options for flow routing include Steady Flow, Kinematic Wave, and Dynamic Wave Routing.

- Steady Flow Routing: Within each time step flow is uniform and steady, and thus it simply translates inflow hydrographs at the upstream end of the conduit to the downstream end with no delay or change in shape.
- Kinematic Wave Routing: Solves the continuity equation along with a simplified form of the momentum equation in each conduit. Cannot account for backwater effects, entrance/exit losses, flow reversal, or pressurized flow. Moderately large time steps, on the order of 1 to 5 minutes.
- Dynamic Wave Routing: Solves the complete one-dimensional Saint Venant flow equations (continuity and momentum equations for conduits and volume continuity equation for nodes). Small time steps are required, on the order of thirty seconds or less.

Ground Water Routing

Aquifers are sub-surface groundwater areas used to model the vertical movement of water infiltrating from subcatchments that lie above. Permit the infiltration of groundwater into the drainage system or exfiltration of surface water from the drainage system depending on the hydraulic gradient that exists.

- Represented by a un-saturated zone (upper) and a saturated zone (lower)
- Parameters of an aquifer can be shared by several subcatchments; No exchange of groundwater between subcatchments; a node can exchange groundwater with more than one subcatchment

Water Balance Equations

$$Vunsat = Vunsat_0 + f_I - f_{EU}$$

$$Vsat = Vsat_0 + f_U - (f_L + f_{EL} + f_G)$$

- Vunsat is the volume of the unsaturated zone at the end of the time step
- $Vunsat_0$ is the volume of the unsaturated zone at the beginning of the time step
- f_I is the infiltration from the surface
- f_{EU} is the evapotranspiration from the upper zone which is a fixed fraction of the unused surface evaporation
- f_U is the percolation from the upper to lower zone which depends on the upper zone moisture content and the depth of the unsaturated zone.
- f_{EL} is the evapotranspiration from the lower zone which is a function of the depth of the unsaturated zone
- f_L is the seepage from the lower zone to the deep groundwater which depends on the lower zone depth (this water is lost from the model)
- f_G is the lateral groundwater interflow to the conveyance network which depends on the lower zone depth as well as the depths in the receiving channel or node

Additional Information

The following attributes about the aquifer can be entered into the Aquifer Editor:

- Porosity (volumetric fraction)
- Wilting Point (volumetric fraction)
- Field Capacity (volumetric fraction) soil moisture content after all free water has drained
- Conductivity or the soils saturated hydraulic conductivity
- Conductivity Slope
- Tension Slope – slope of soil tension versus soil moisture content
- Upper Evaporation Fraction – ET from the upper unsaturated zone
- Lower Evaporation Depth – Max depth below the surface at which evapotranspiration from the lower saturated zone can still occur.
- Lower Groundwater Loss Rate – Rate of percolation from saturated zone to deep groundwater
- Bottom Elevation – bottom of the aquifer
- Water Table Elevation – water table at start of simulation
- Unsaturated Zone Moisture – content at start of simulation
- Upper Evaporation Pattern – name of a monthly time pattern used to adjust for ET

Groundwater Flow Editor is used to link a subcatchment to a parent aquifer and to a node of the conveyance system that exchanges groundwater with the subcatchment. It also specifies coefficients that determine the rate of lateral groundwater flow between the aquifer and the node:

$$Q_L = A1(H_{GW} - H_{CB})^{B1} - A2(H_{SW} - H_{CB})^{B2} + A3(H_{GW}H_{SW})$$

- Q_L is the lateral groundwater flow (cfs per acre or cms per hectare)
- H_{GW} is the height of the saturated zone above bottom of the aquifer (ft or m)
- H_{SW} is the height of surface water at receiving node above aquifer bottom (ft or m)
- H_{CB} is the height of channel bottom above aquifer bottom (ft or m)

Additionally, the rate of seepage to the deep groundwater is:

$$Q_D = LGLR * H_{GW}/H_{GS}$$

- Q_D is the seepage rate (in/hr or mm/hr)
- LGLR is the lower groundwater loss rate assigned in the subcatchment’s aquifer (in/hr or mm/hr)
- H_{GS} is the distance from the ground surface to the aquifer bottom (ft or m)

APPENDIX I: Hydrologic comparison template for VFLO.

VFlo

<u>General Information</u>

Model History

Developed in 1988 by Baxter Vieux for his Agricultural engineering dissertation at Michigan State University as a GIS application of finite element analysis of hydrologic response areas. It used Arc-Info GIS and the finite element Galerkin formulation to solve the kinematic wave equation for overland flow in a watershed. A key feature of the model was the ability to predict flow rates and stage in every grid cell of a gridded map defined by the hydraulics of overland and channel flow. The integrated hydraulic network made it possible to represent local and mainstem flows with the same model setup simultaneously. It also made it useful for both urban and natural watersheds, reservoir inflow, flood prediction, hydrologic analysis of land use change, and climate change.

Vieux and Associates, Inc. started in 1992, at which point VFlo was a commercial product. Upgrades to the model seemed to occur once it became a commercial product as the user manual states that the model was developed in 1993 for the U.S. Army Corps of Engineers, Construction Engineering Research Laboratory (CERL). The developers extended the solution of the initial model to a watershed domain and later added channel routing, Green and Ampt infiltration, and distributed radar rainfall input.

Source (Open/Proprietary)

Proprietary. Costs are not listed on website, but subscription cost depends on number of seats. Bundled with Rainvieux products which FEWS currently operates.

Contact Jean Vieux (jean.vieux@vieuxinc.com) with questions regarding acquisition or support.

Maintenance

Vieux & Associates, Inc.

Model Uses

25. Hydrology, nutrient transport, sediment transport, other pollutants?
    Hydrology is main purpose, including flood prediction, impacts of land use change, and climate change. Can be used for both design storm and continuous simulation models. Early uses were linked to AGNPS for sediment and nutrient transport with a daily time step. Other uses were common agricultural chemicals including pesticides and herbicides.

26. How are SCMs incorporated?
    Vary parameters in the BOP (basin overland properties) file which holds all the model parameters such as roughness, hydraulic conductivity, infiltration, etc. A Pipes Extension provides a secondary drainage network for diversions to tunnels or detention basins using hydraulic inlet rating curves, percent diversions, or from SWMM pipe-node configuration. Reservoirs are also simulated and could be used for detention ponds. Otherwise, no direct water quality control structures because no direct water quality.

27. Duration of Model Run
    a. Minimum/Maximum Time Step – Undocumented min/max. For solving the hydrograph, VFlo computes the time step subject to Courant condition for the rainfall input and parameters governing the hydraulics of overland and channel flow (i.e. roughness and slope). The user can modify these parameters or the rainfall input to reduce or remove very high rainfall intensities and reduce instabilities if they occur. Basically, driven by the kinematic wave formula for overland flow.

Calibration Method

Manual calibration. Several methods are suggested in order to calibrate the model which include saving a visual reference of generated hydrographs until a suitable calibration scheme is determined, the Ordered Physics-based Parameter Adjustment (OPPA) method, or differential calibration by river reach.

A Calibration Factors panel is used to manipulate parameters during calibration. This feature includes slider bars for roughness, hydraulic conductivity, wetting front, soil depth, initial saturation, abstraction, channel width, channel side slope, channel baseflow, and rainfall. Calibration factors may be applied to an entire basin, a sub-basin, a few selected cells, or an individual cell, depending on which cells are selected when calibration factors are applied.

Suggested Tools for Data Entry

- For watershed building, the AutoBOP software makes things easier in creating the drainage network, and importing parameter maps. A high-resolution DEM and GIS software like ArcGIS 9.2 with Spatial Analyst are required (other combinations or WMS will work).
- You can also create a basin model manually in Vflo by drawing flow directions and connecting upstream grid cells to downstream with other parameter maps loaded as geographic map layers of hydraulics and infiltration parameters used to designate roughness and hydraulic conductivity.
- All cell properties representing D8 flow directions and parameters can be produced externally with GIS and imported.

Watershed Configuration

Land Surface

Area to be simulated: Basin. A basin model can be constructed in one of four ways. The AutoBOP procedure may be used to develop a drainage network, establish the domain, and import parameter maps (DEM and key shapefiles required). A basin model can be manually developed in VFlo, GIS software can be used to develop parameter maps prior to importing to VFlo (DEM, gridded soil map, gridded land use map, key shapefiles required), or a custom BOP file can be created by contacting Vieux and Assoc.

Land unit distribution: Gridded

Hydrologic unit(s) of land whose topography and drainage system elements direct surface runoff to a single discharge point: Overland Cell

- Properties of overland cells include roughness, slope, and full set of infiltration parameters.
- Normal depth is governed by Manning's equation, assuming uniform flow depth over the grid cell.
- Minimum/Maximum Unit Size: Limited by the DEM.

Distribution of Impervious/Pervious Land: Cells are designated as impervious/pervious with overland cell parameters that match.

Flow Pathway

Inflow or Discharge Points: As a gridded system, a flow direction map is used to direct overland flow and channel flow. Thus, inflow happens in overland cells or channel cells along the flow direction map. This mapping can be done in GIS prior to entering into VFlo or it can be a process run inside of VFlo.

- Watch points can be assigned for cells of interest.

Primary flow pathway (channel, pipes, etc.): Channel, Rated channel, cross section, reservoir cells

- Channel Cells – Represent channels, streams, and other pathways. These are trapezoidal cells which use channel width and channel side slope to define cross sections and generate stage discharge relationships for the cell. Properties include roughness, slope, channel width, channel side slope, and baseflow (lateral inflow from groundwater)
- Rated Channel Cells – Rating curves are provided by user and used to simulate the channel geometry. Discrete pairs of stage-area and stage-discharge are typed into Vflo manually or loaded from a text file. Other properties include slope, baseflow, and infiltration parameters.
- Cross Section Cells – Measured channel geometry by ordered pairs of distance and elevation are entered to synthesize the rating curve. Properties include roughness, slope, baseflow, base elevation, and cross section pairs of distance and elevation.
- Reservoir Cells – Used to model a detention basin or an uncontrolled reservoir using storage-stage and stage-discharge curves. Storage characteristics are entered by the user including an initial storage which is the amount of storage available before discharge occurs.

Additional Information

Base cells are the default cells in VFlo. They do not have any parameters other than flow direction. Typically used to model shallow water in wetlands, marshes, and lakes. Flow that passes through a base cell will move through the cell based on the kinematic wave celerity ($c^2 = gh$, where g is the acceleration due to gravity and h is the water depth).

Weather (include time step for applicable fields)
Rain: gridded rainfall produced from radar, point rainfall measured at rain gauge locations, or hypothetical design storms such as the SCS Type II.

Temperature: NA.

Wind Speed: NA.

Relative Humidity: NA.

Solar Radiation: NA.

Forecast data: NA.

Snow: NA

Climate Change: NA

Surface Runoff and Soil Routing

Inputs/Outputs

Overland flow cell inputs = precipitation + overland flow from upstream cell
Overland flow cell outputs = infiltration + evapotranspiration + surface runoff

Precipitation

Rain (defined in the weather section above)

Surface Runoff

Runoff is generated once rainfall rates exceed infiltration rates or when soil is saturated (wetting front reaches the soil depth). Runoff occurs from overland cell to overland cell and from overland cell to channel cell. Cell type establishes which set of kinematic wave equations will be used to calculate runoff. Equations are solved by finite element method. For surface runoff (overland flow cells):

$$\frac{\partial h}{\partial t}+\frac{S_o^{1/2}\partial h^{5/3}}{n\partial x}=R-I$$

- h is the depth
- S_o is the land surface slope
- n is the roughness
- R is rainfall rate
- I is infiltration rate

Infiltration

Single layer soil model. Green and Ampt infiltration routine where infiltration properties are entered by user. Soil moisture is tracked in each cell, determined from the infiltration volume that is redistributed at the end of each day from the wetting front volume. Soil moisture depleted by ET rate and replenished by infiltration. Inputs include:

- Hydraulic conductivity (saturated)
- Wetting front - wetting front suction head, or average capillary potential
- Effective porosity – difference between total porosity and residual soil moisture content
- Soil depth – depth to which infiltration may occur, should be based on the limiting layer which may not be the same source everywhere (water table, impermeable layer, etc)
- Initial saturation
- Abstraction – equivalent to the amount of rainfall that must occur before any runoff may be generated for a cell, not used in a continuous simulation
- Impervious – percent of a cell area that is impervious to infiltration
- Evapotranspiration

Evapotranspiration

User has one of three options for ET inputs:

- Constant Value – same value for all times for all cells
- Single Time Series – load ET from a single file
- Spatially Variable Time Series – load multiple ASCII files

Percolation

There is no flow from the soil into a deep aquifer. Once water is infiltrated it is lost.

Lateral subsurface flow

There is no flow modeled in the subsurface. A baseflow property can be input into a channel cell to represent groundwater re-entering the stream.

Channel Routing

Channel cells route the stream flow. The following equation is solved:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q$$

- A is cross-sectional area
- Q is discharge or flow rate in channel
- q is the rate of lateral inflow per unit length in the channel

There are two options to solve the above equation.

- Modified-Puls – routes flow from one channel cell to the next using the stage-volume and stage-discharge relationship defined by the rating curves or trapezoidal cross-section for the channel. Outflow hydrograph for one grid cell becomes the inflow hydrograph in the next channel cell downstream.
- Kinematic wave approximation in the form of the Jones formula, where C is wave celerity (speed of wave):

$$v = \frac{\partial h}{\partial x} = -\frac{1}{C}\frac{\partial h}{\partial t}$$

Ground Water Routing

Water infiltration is tracked and leaves the system.

Water can be reintroduced into the stream from groundwater using the Baseflow in the hydraulic properties in channel cells. Channel cells can be treated as losing streams by giving the Baseflow parameter a negative number in the hydraulic properties.

There is no true ground water routing in this model.

Additional Information

Hydraulic Properties that can be entered for a cell:
Flow direction – E,SE,S,SW,W,NW,N,NE, and none; derived from DEM or manually
Roughness – manning's roughness coefficient for a cell, minimum is 0.01
Slope – elevation gradient from one cell to another; derived from DEM
Channel width – property of channel cells; width of channel at base
Channel side slope – property of channel cells; ratio between the change in distance over the change in elevation for channel sides
Baseflow – lateral inflow from groundwater and/or outflow to groundwater
Base elevation
Initial storage
Rating curve (area-stage, stage-discharge, or storage-stage curves)
Channel cross sections